Control of the Micro-Bunching Instability in Storage Rings, Using Control of Chaos Strategy

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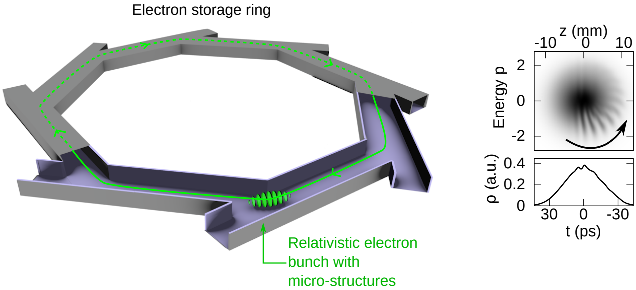
Microbunching instability

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



Microbunching instability

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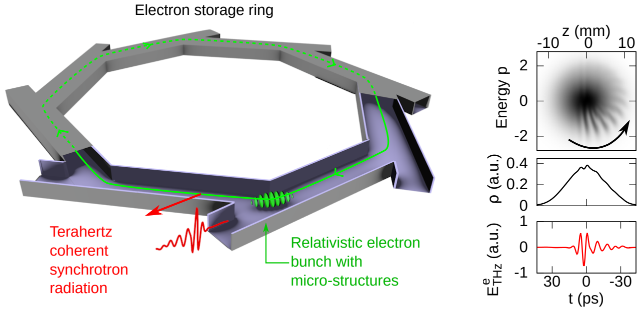
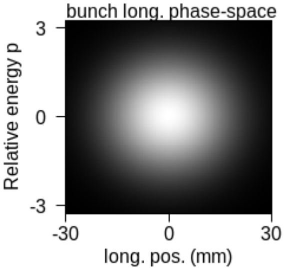
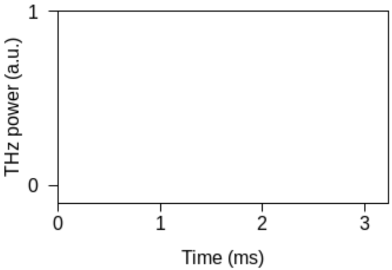


- Effect of the microstructures ⇒ emission of intense coherent THz pulses (typ. >10000 times stronger than normal incoherent synchrotron radiation)
- Observation in a large number of storage rings
  (NLSL, SURF III, BESSY II, ALS, SLAC, UVSOR II, ELETTRA, ANKA/KARA, CNL, DIAMOND, SOLEIL, etc.)

Simulations of the electron bunch dynamics

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





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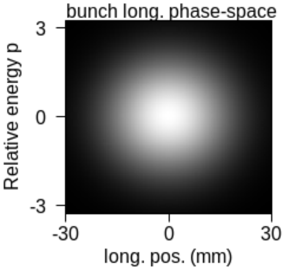
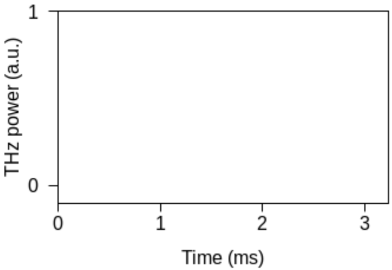
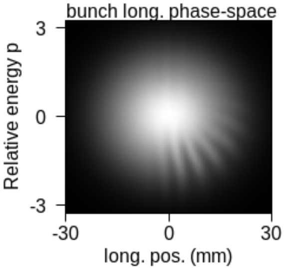
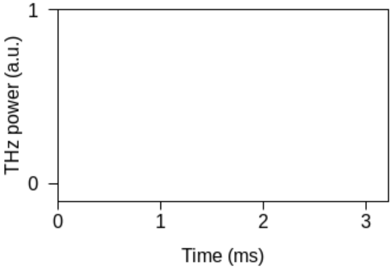




- **An other co-existing mathematical solution**
  regular dynamics
  but with unstable properties
  (not observable directly)





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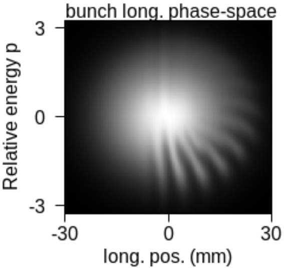

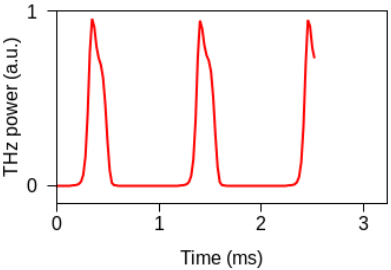

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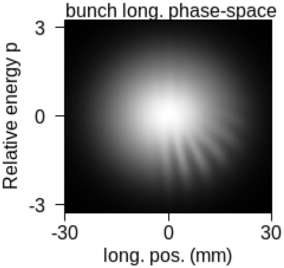
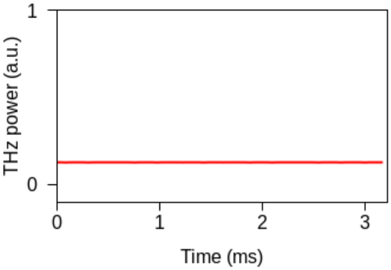
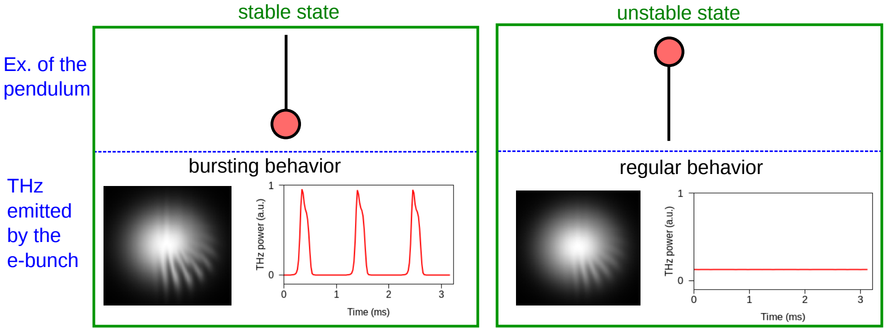




Stability & control of unstable states

- Analogy between a relativistic electron bunch and a pendulum system



- For complex systems (as chaotic systems), possibility to stabilize the unstable state(s) thanks to a feedback loop [Ott, Grebogi and Yorke, Phys. Rev. Lett. **64**, 1196 (1990)]
- Weak energy to maintain the stabilization (in principle just higher than the noise level)

⇒ Is it possible to to stabilize the **regular unstable** state and have quasi-constant THz ?

Modelling the electron beam dynamics

- 1D Vlasov-Fokker-Planck (VFP) equation [Venturini and Warnock, Phys. Rev. Lett. **89**, 224802 (2002)]

$$\frac{\partial f(q,p,\theta)}{\partial \theta} - p\frac{\partial f}{\partial q} + \frac{\partial f}{\partial p}\left[q - I_c E_{wf}\right] = 2\varepsilon \frac{\partial}{\partial p}\left(pf + \frac{\partial f}{\partial p}\right)$$

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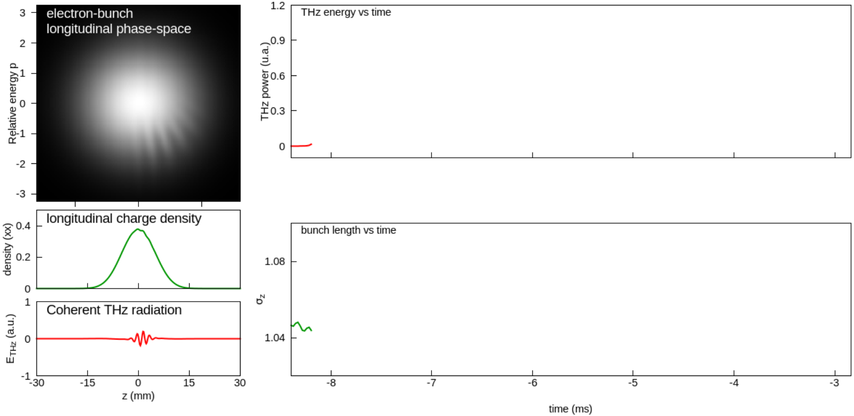
- Results : from longitudinal phase-space to THz emission



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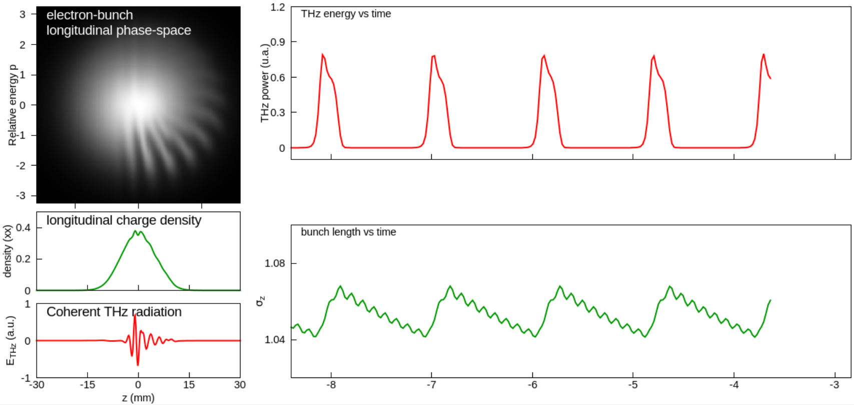


Implementation of the feedback loop

- Feedback loop between
  - ▷ the THz power ≡ "strength" of the micro-structures
  - ▷ the slope of the RF field ≡ bunch length

Modified VFP equation :

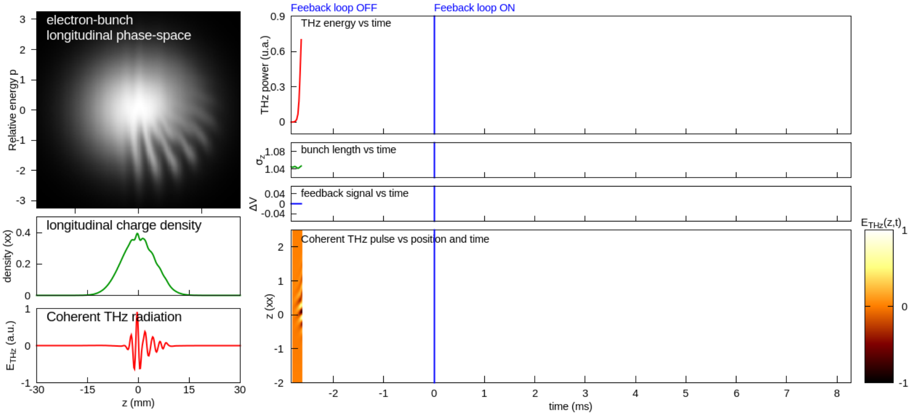
$$\frac{\partial f(q,p,\theta)}{\partial \theta} - p\frac{\partial f}{\partial q} + \frac{\partial f}{\partial p}\left[\overbrace{\left(q\left[1+\underbrace{\Delta q(\theta)}_{\text{feedback}}\right]\right)}^{\text{RF slope}} - I_c E_{wf}\right] = 2\varepsilon\frac{\partial}{\partial p}\left(pf + \frac{\partial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

- 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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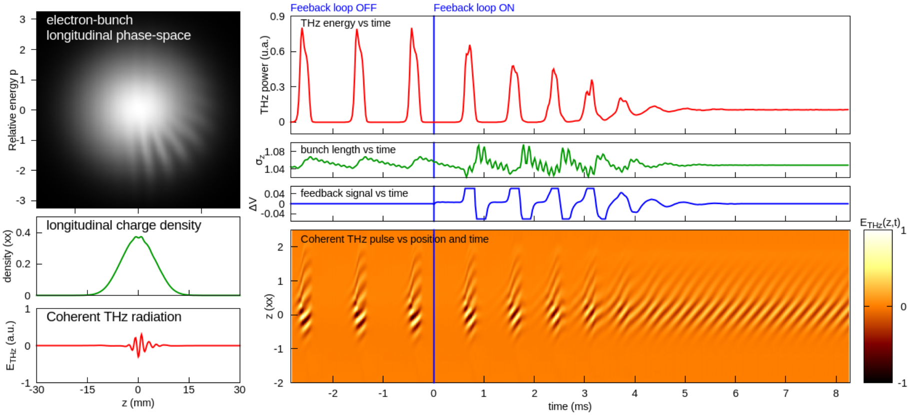

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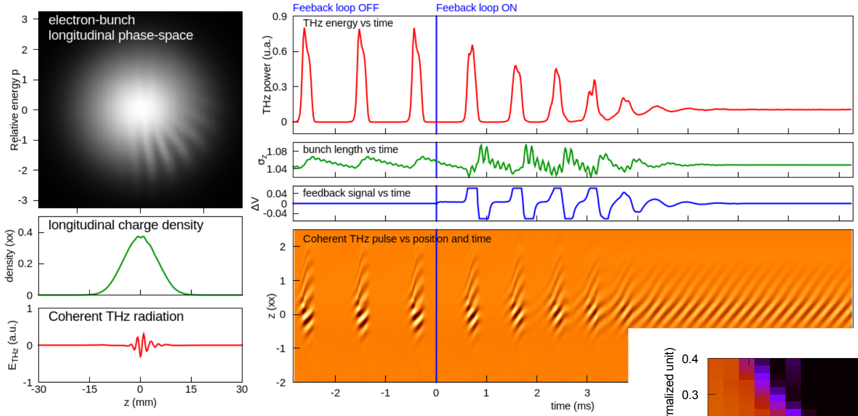
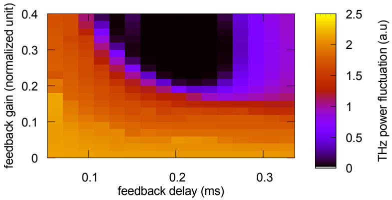
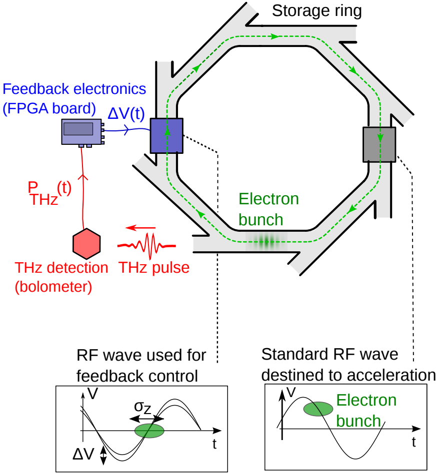


- THz fluctuations vs. feedback parameters $(\tau,\ G)$ $\rightarrow\rightarrow\rightarrow$

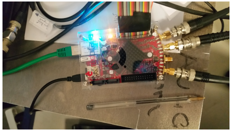


Experimental setup @Synchrotron SOLEIL



- Synchrotron SOLEIL (circumference : 354 m)

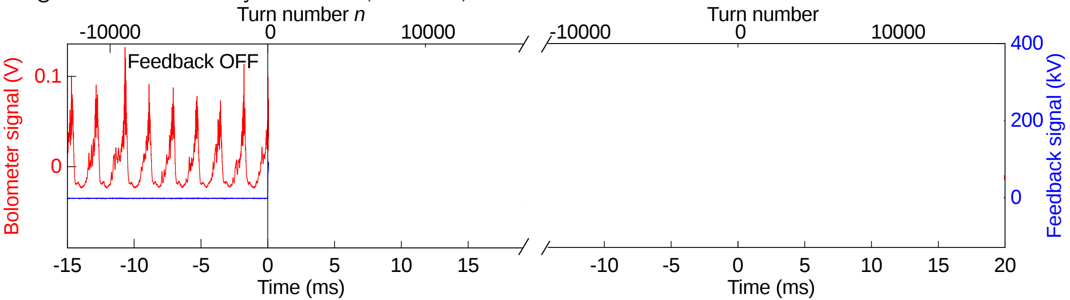
- THz detection @AILES beamline using a InSb bolometer (1-μs response time)
- Feedback loop using an FPGA board (Red Pitaya)



- 1 RF cavity @zero-crossing

Application of the feedback

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



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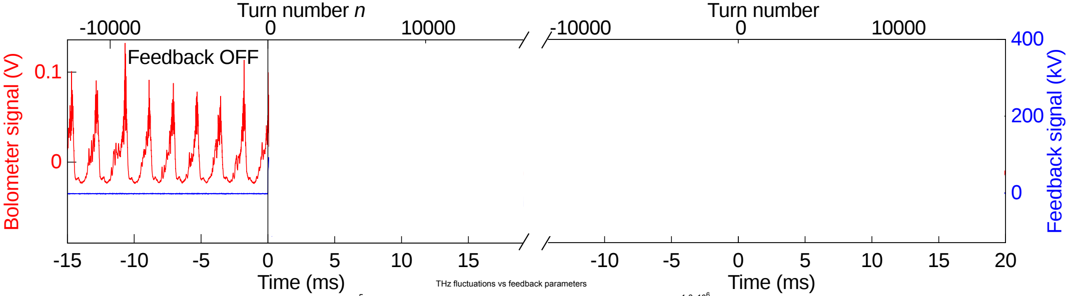
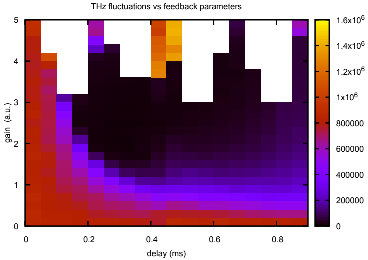


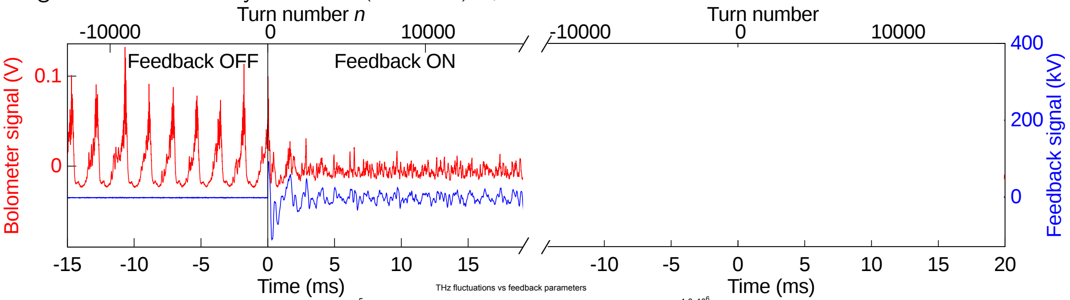
- THz fluctuations vs. feedback parameters (τ, G)

  (10 minutes for 40 × 40 parameters scan)



Application of the feedback

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



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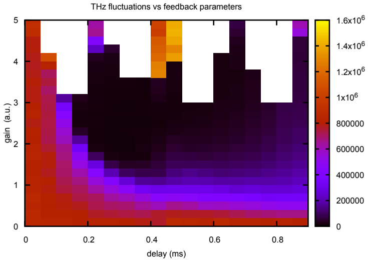

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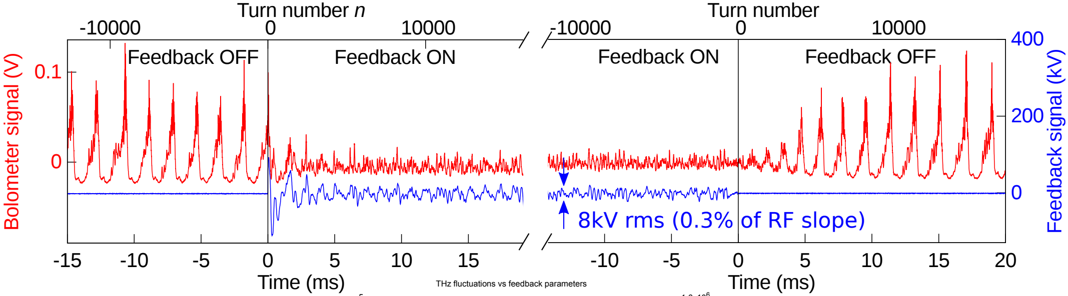

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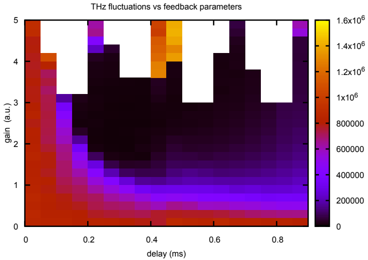
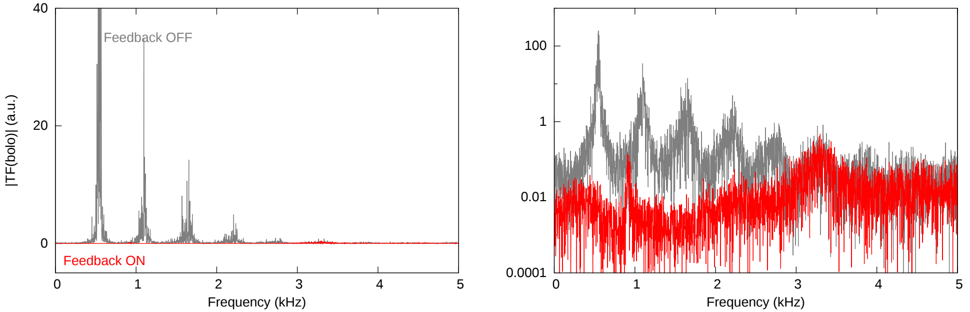


THz signal with/without feedback

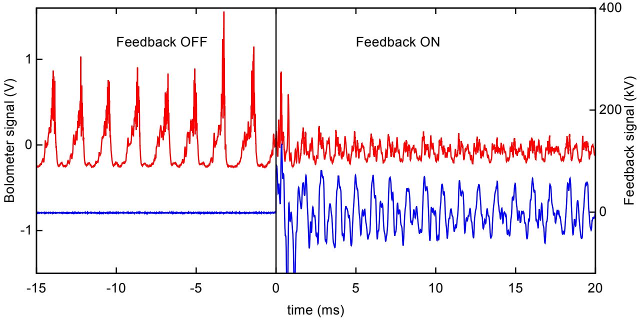
- Power spectra of the bolometer signal (i.e. THz signal)



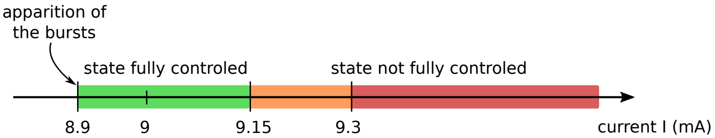
→ suppression of the fluctuations by up to more than **40 dB**
Note : RF amplitude modulation bandwidth ∼ 3.5 kHz

Efficiency of the control

- THz signal @9.3 mA

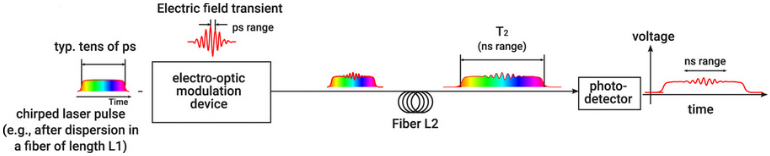


- Feedback efficiency vs. current

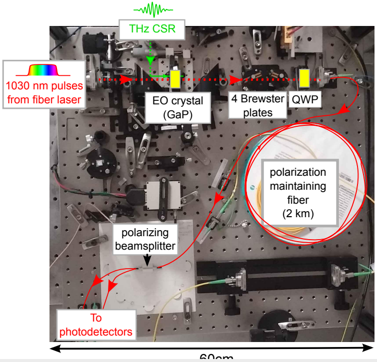


Direct observation of the THz pulses turn-by-turn

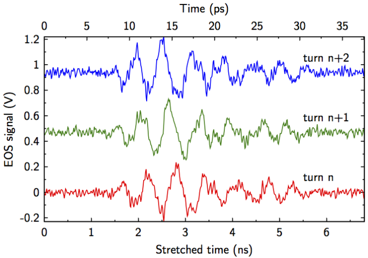
- Detection principle : electro-optic sampling + time-stretch



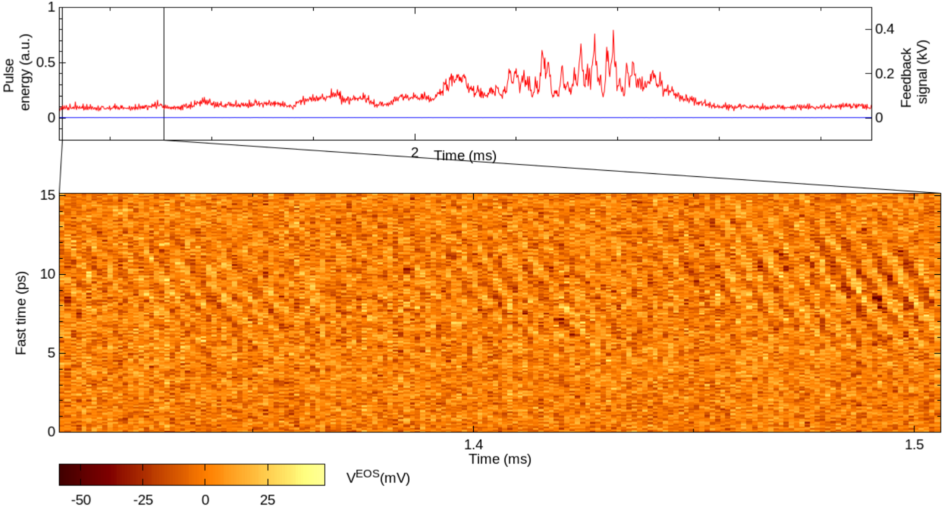
[Roussel et al., SciRep. **5**, 10330 (2015)], [Szwaj et. al., RSI **87**, 103111 (2016)], [Evain et al., PRL **118**, 054801 (2017)]



3 consecutive single-shots



Direct observation : **without** feedback



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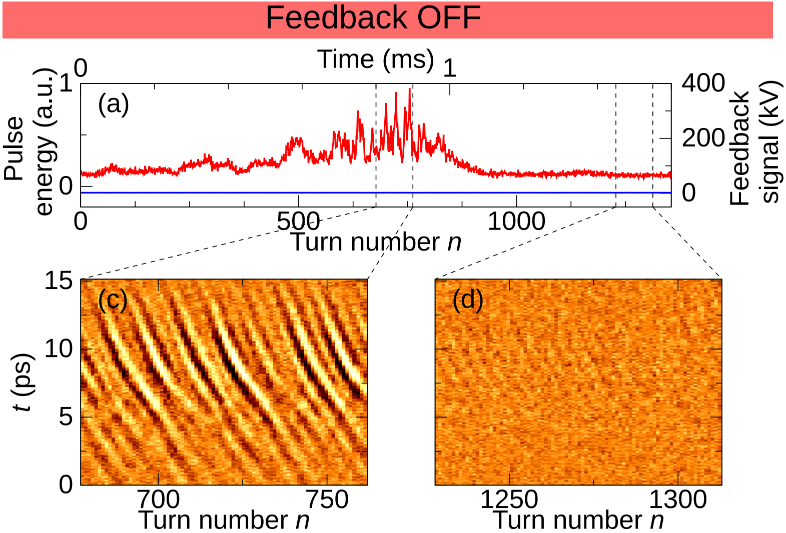

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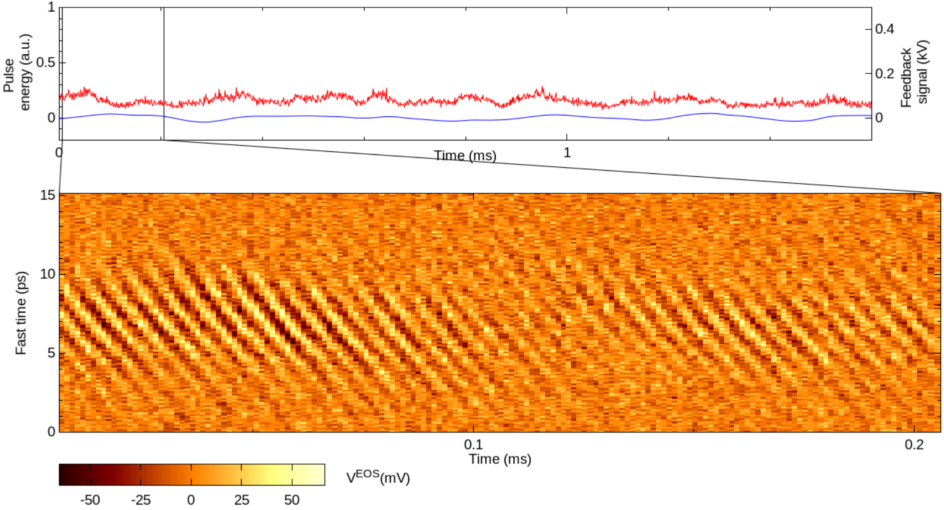

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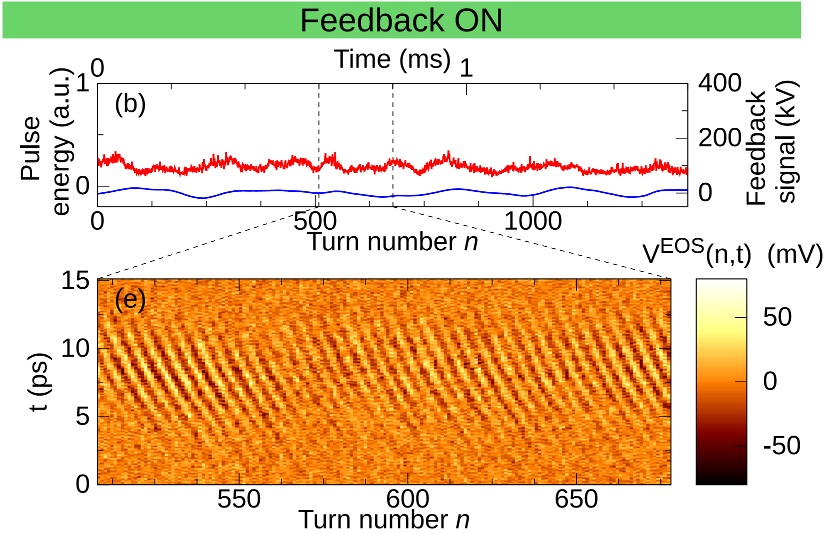

Conclusion & perspectives

- 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)]

- **Control over a limited current range** ⇒ understand what are the limitations and how to remove them
  - ▷ more feedback loops using one or several observables
  - ▷ other types of feedback
  - ▷ machine learning strategy or multi-objective optimization (MOGA)
  - ▷ ...