Generation and Control of Stable CSR Bursts

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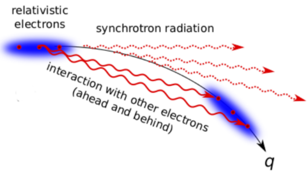
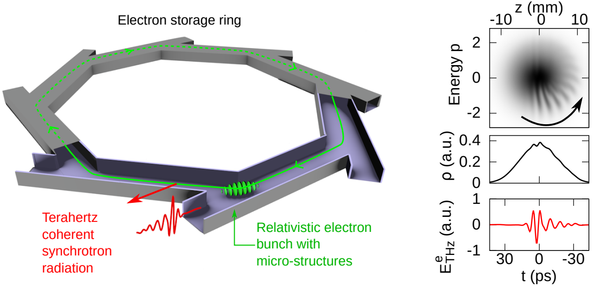
Workshop on Longitudinal Electron beam Dynamics for coherent Sources 2024 (LEDS 2024)

Outline

Microbunching instability - introduction

- Microbunching instability appears when the number of e- is higher than a threshold value (due to the interaction between the e- of a bunch and their radiation)
- Characterized by **spontaneous apparition of micro-structures** in the long. phase-space of the bunch





- Permit the emission of a **strong THz coherent synchrotron radiation** (CSR) at the micro-structure wavelengths

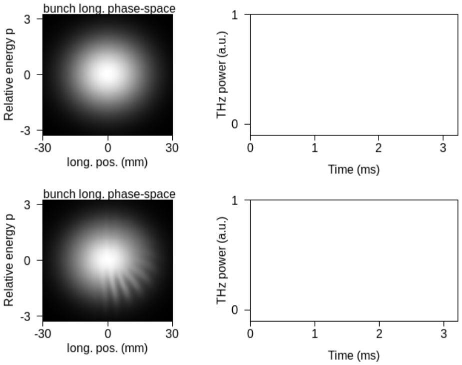
Microbunching instability - introduction

- Observed in a large number of storage rings (NLSL, SURF III, BESSY II, ALS, SLAC, UVSOR II, ELETTRA, ANKA/KARA, CNL, DIAMOND, SOLEIL, MLS, etc.) - and expected in low-emittance rings
- **These studies :** based on the manipulation of the bunch dynamics (via RF cavity modulation) to change the characteristics of the micro-bunching instability and the emitted CSR
- **Motivations** : fundamental part (understand the dynamics of this complex system) and more applied part (for the dev. of accelerator physics and THz sources)

Let us **name** the concepts from the dynamical point of view (more important than it seems)

- **Experimentally observed** solution (bursts)
  Conceptually : an **Attractor**
  If we perturb the system
  $\rightarrow$ back to the same solution
  (obviously... this is why we observe it...)

- **"Math says that :"**
  1) Other solutions usually co-exist
  2) That are "unstable in Lyapunov sense"



Question : is this "regular&Lyapunov-unstable" solution useful for anything ?
or is it just a mathematical curiosity ?

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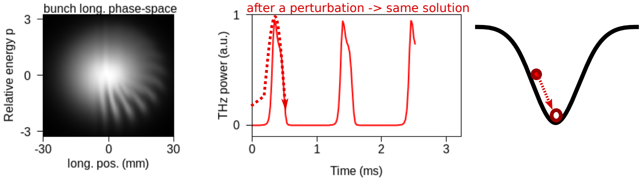

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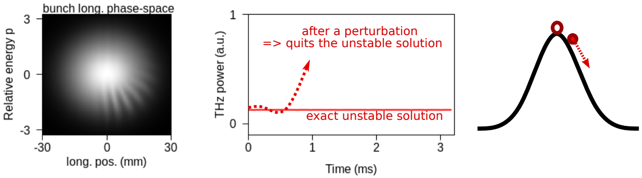
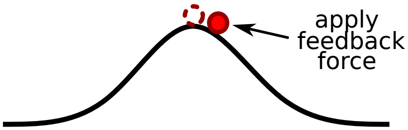


Question : is this "regular&Lyapunov-unstable" solution useful for anything ?
or is it just a mathematical curiosity ?

Stabilization of a pre-existing solution

- For trivial or 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)]

- Principle : apply a force depending on the distance to the desired state (feedback).



- Major consequence : the required power → ZERO once the transient have disappeared
Crucial here as the power involved at SOLEIL is a fraction of MEGAWATT...

- Many examples : lasers, chemistry, electronics, biology, accelerator context (FEL oscillators)

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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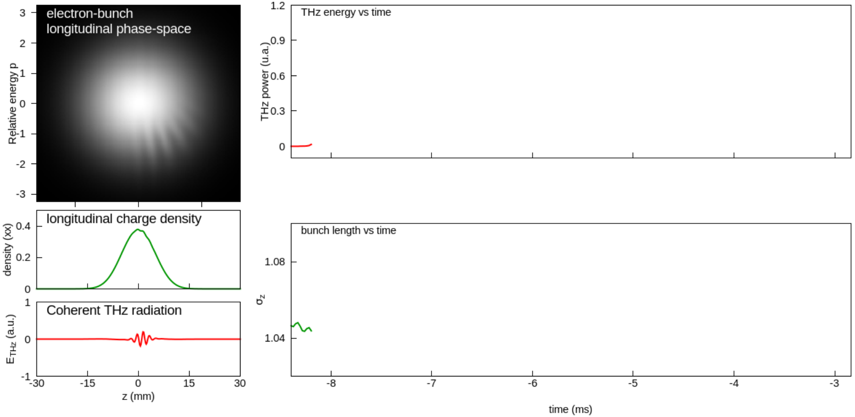
- Results : from longitudinal phase-space to THz emission



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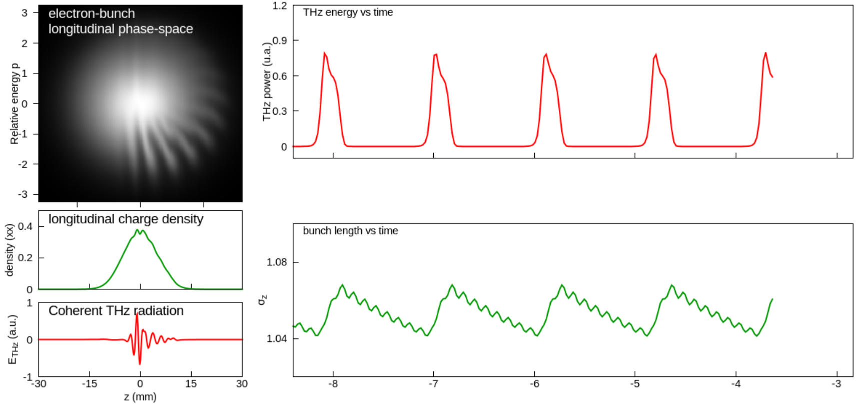

Control principle

- feedback loop between
  - the THz power (indication of the "strengh of the micro-structures")
  - the slope of the RF cavities (which changes the bunch length = "gain of the instability")

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

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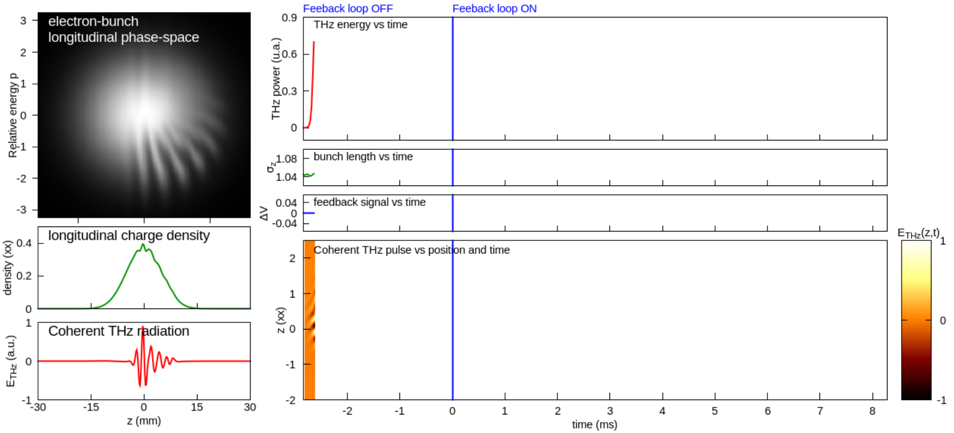
- feedback signal :
  - delay feedback [K. Pyragas, Phys. Lett. A, 1992] (Pyragas method)
  - $\Delta V(t) = G(P_{THz}(t) - P_{THz}(t-\tau))$
  - advantages :
    - no need to make assumption on the solution to stabilized
    - the feedback signal tends to zero when feedback is achieved

Control of the microbunching instability : numerical results



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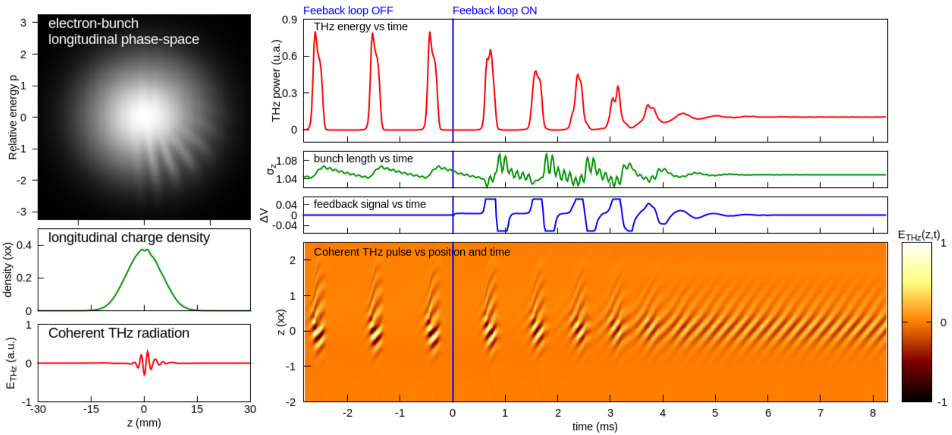

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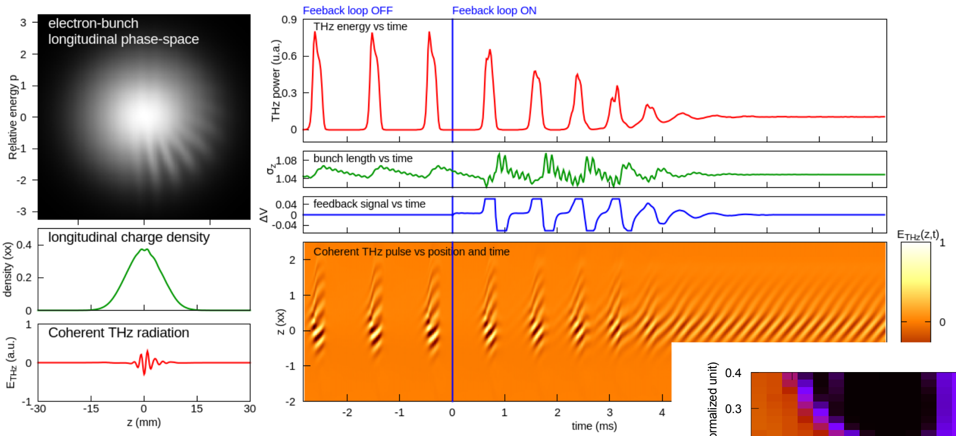
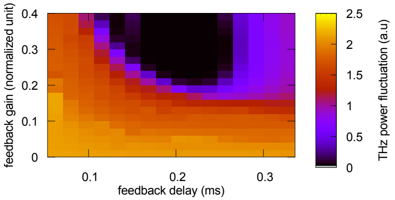
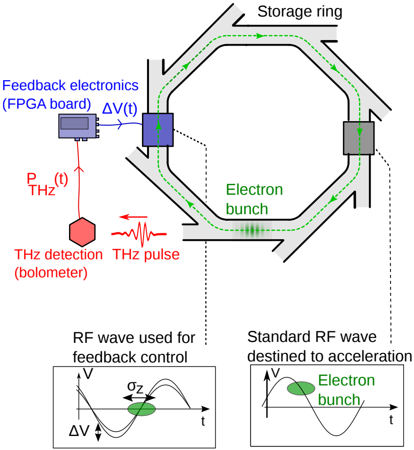


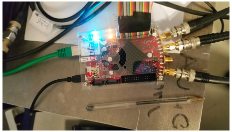
- THz fluctuations vs. feedback parameters (τ, G) $\rightarrow\rightarrow\rightarrow$



Experimental setup @Synchrotron SOLEIL



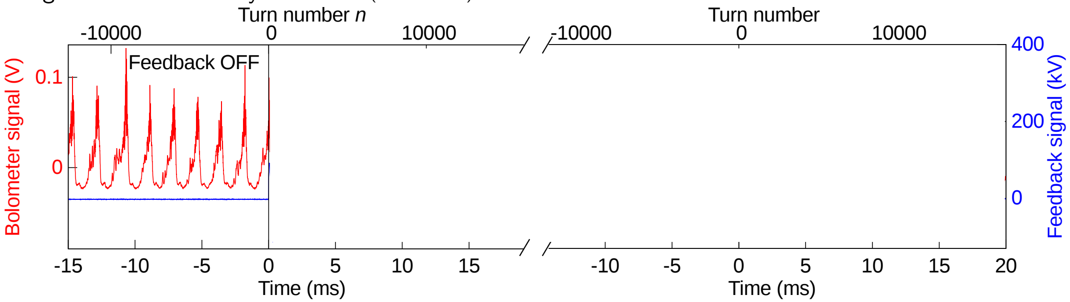
- THz detection @AILES beamline using a InSb bolometer (1-μs response time)
- Feedback loop using an FPGA board (Red Pitaya)



- 1 RF cavity @zero-crossing
- Interlock system (cf. after)

Application of the feedback

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



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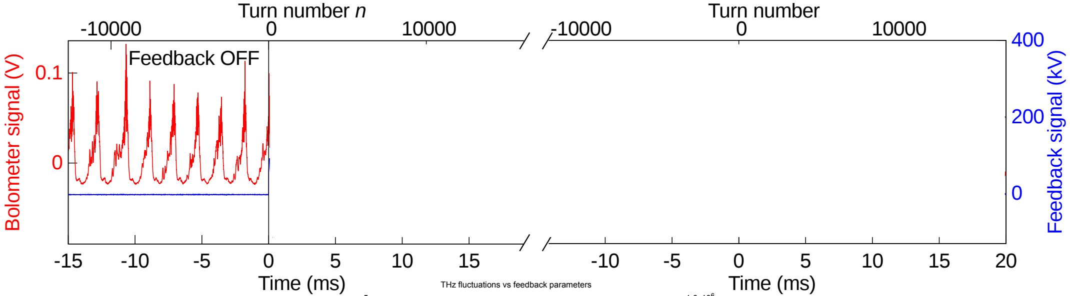

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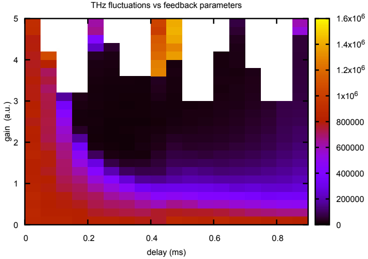
  (10 minutes for 40 × 40 parameters scan)



Application of the feedback

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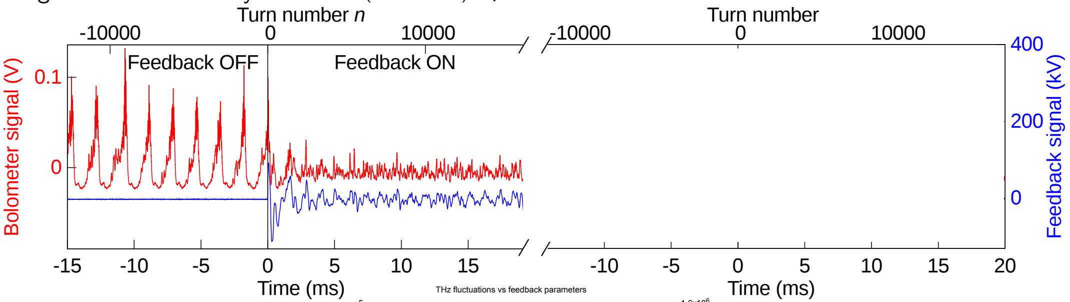

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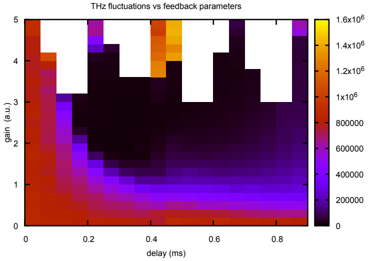

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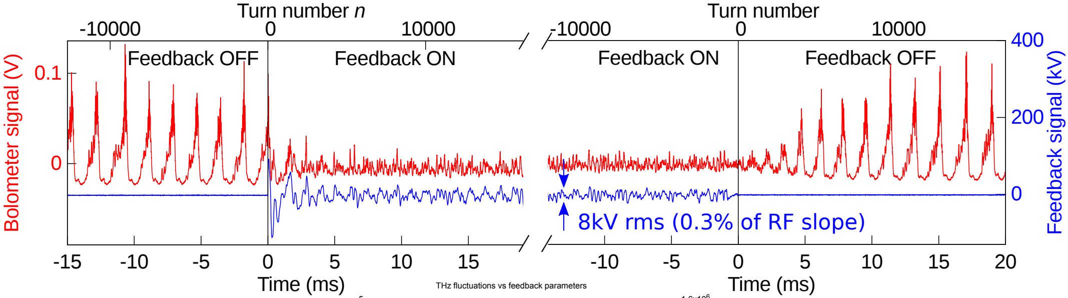

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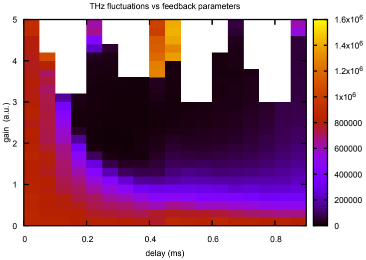
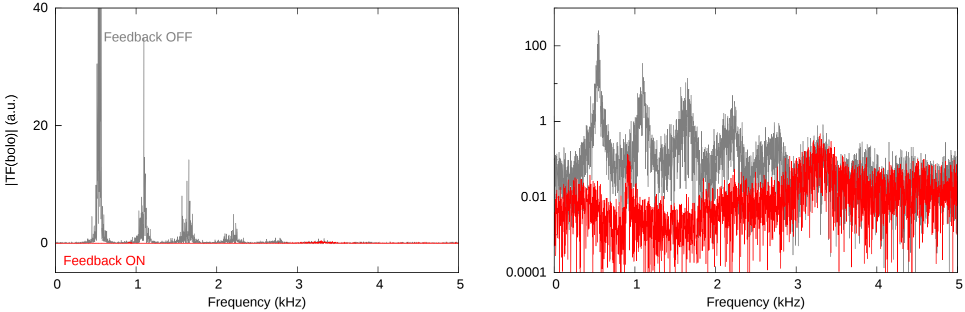


THz signal with/without feedback

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

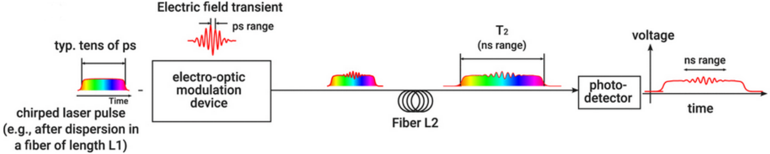


→ suppression of the fluctuations by up to more than **40 dB**
Note : RF amplitude modulation bandwidth ∼ 3.5 kHz

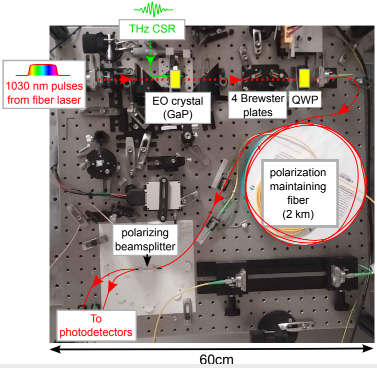
[Evain et al., Nature Physics 15, 635 (2019)]

Direct observation of the THz pulses turn-by-turn

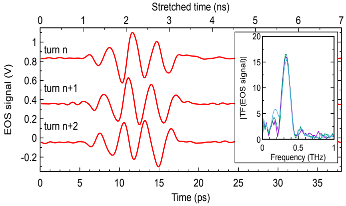
- Detection principle : single-shot electro-optic detection + time-stretch



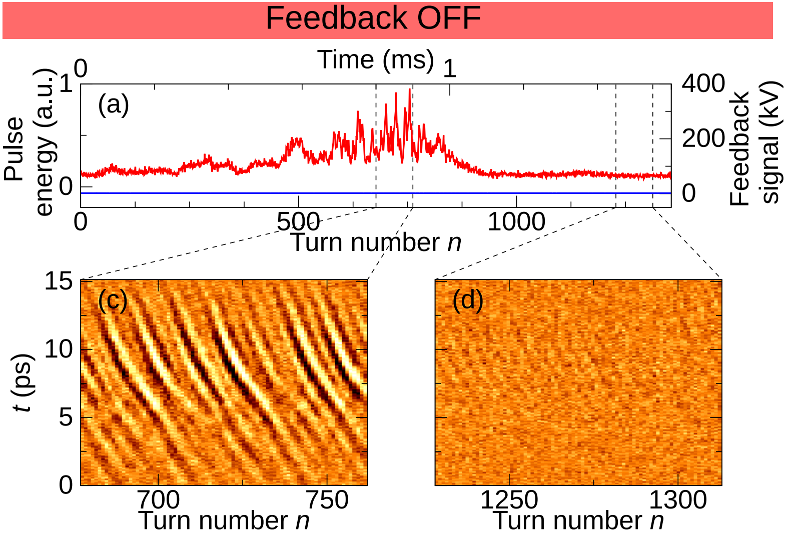
[Roussel et al., SciRep. **5**, 10330 (2015)], [Szwaj et. al., RSI **87**, 103111 (2016)], [Evain et al., PRL **118**, 054801 (2017)]



3 consecutive single-shots



Direct observation : **without** feedback



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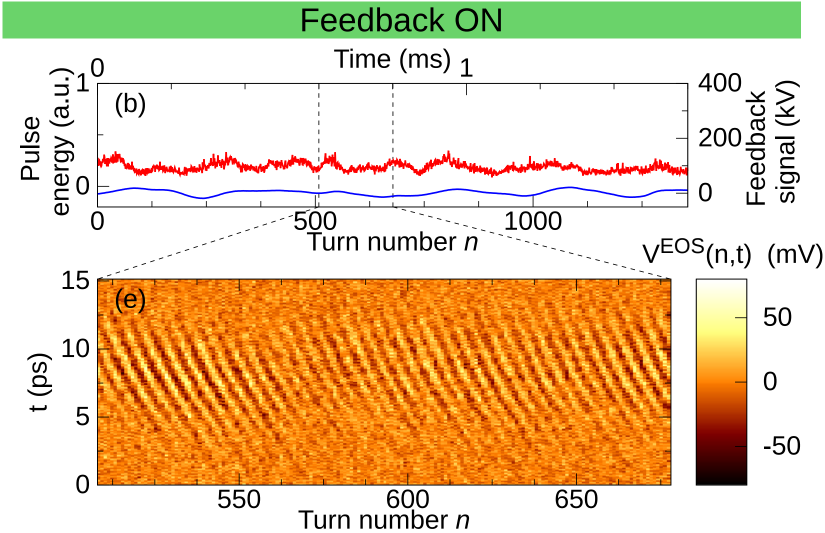
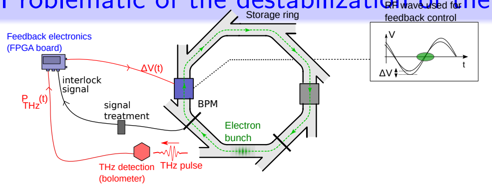
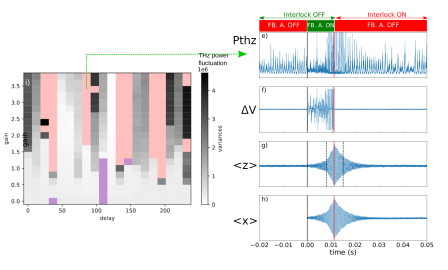


Problematic of the destabilization of the bunch center of mass $< z >$



w/o the feedback on the phase



[C. Evain et. al., Phys. ReV. Acc. and Beams, 2023]

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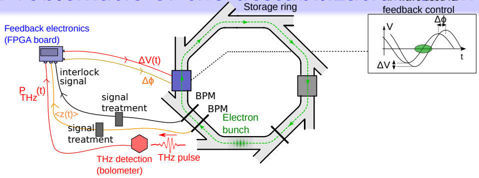

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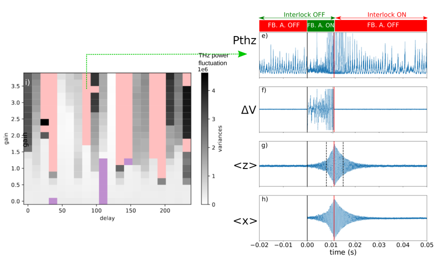

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- Strategy used to prevent strong bunch displacement : additional feedback to stabilize the bunch position
- Feedback loop between :
  - the bunch long. position $< z >$ (from BPM measurment)
  - the phase of the RF cavity (same than the one used for the feedback on the amplitude)
- $\Delta\phi(t) = G_\phi(< z(t) > -z_{ref})$

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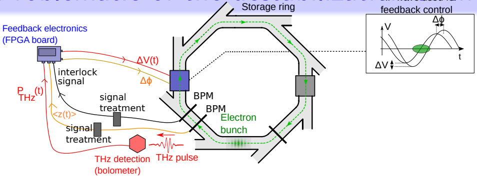

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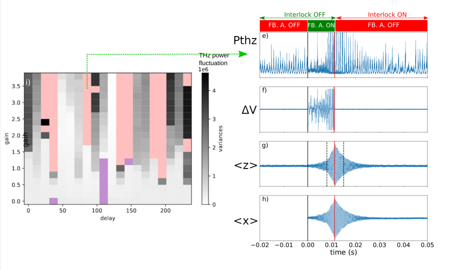

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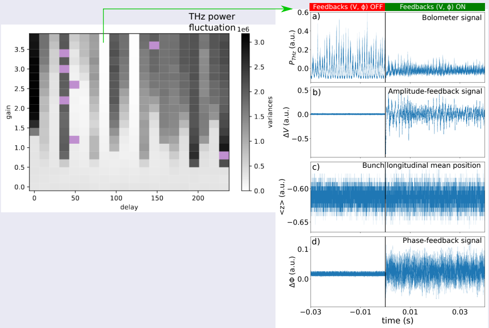
with 2 feeback loops (phase & amplitude of the RF signal)



Intermediate conclusion (on the control part)

- Stabilisation of a pre-existing solution of the e-bunch - having a regular behavior
- possible to have an efficient control near threshold
  [Evain et al., Nature Physics 15, 635 (2019)]
- a **feedback on the phase of the RF-cavity** permits to remove an instability/destabilization induced by the **initial feedback** (on the RF cavity amplitude)
  [C. Evain et. al., Phys. ReV. Acc. and Beams, 2023]
- present challenge @ SOLEIL : find methods to control at higher current

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- strategy : still use a RF cavity in a zero-crossing mode, and modulate its amplitude (**no feedback loop**)

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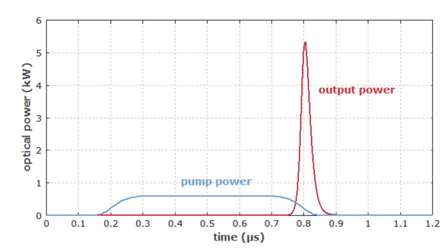
analogy with classical lasers - where intense light pulses can be obtained by the modulating the laser gain



[source : RP-photonics]

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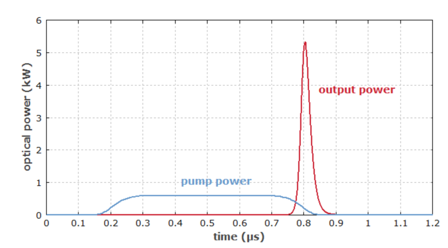

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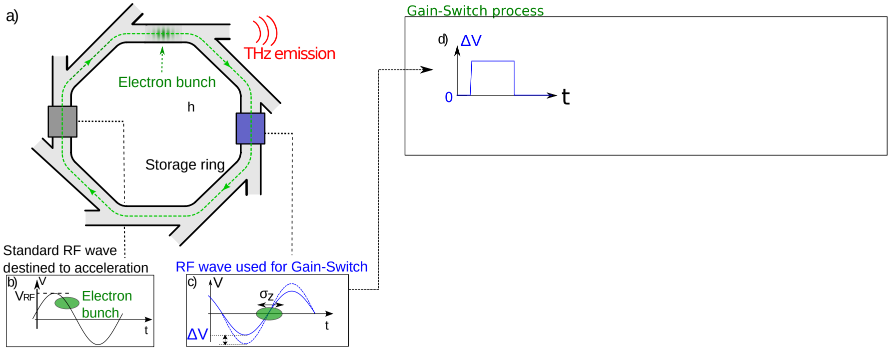
- Here : gain of the microbunching inst. = dimensions of the bunch in the long. phase-space (and possible to act on it by changing the RF signal amplitude)

General view

- modulation of RF-cavity in a zero-crossing mode with a pseudo-rectangular shape (**Not a feedback method**)



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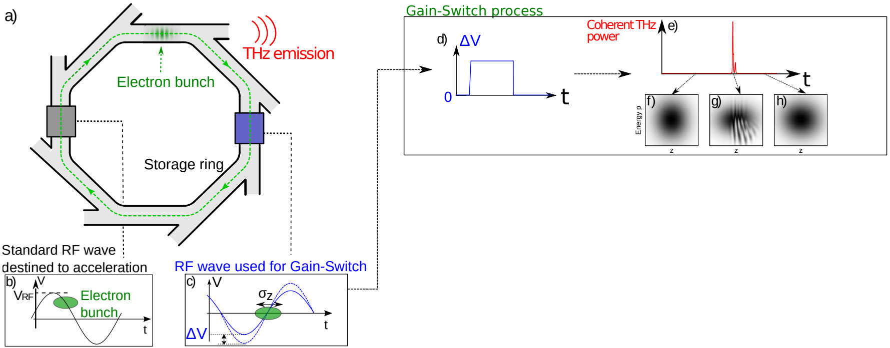

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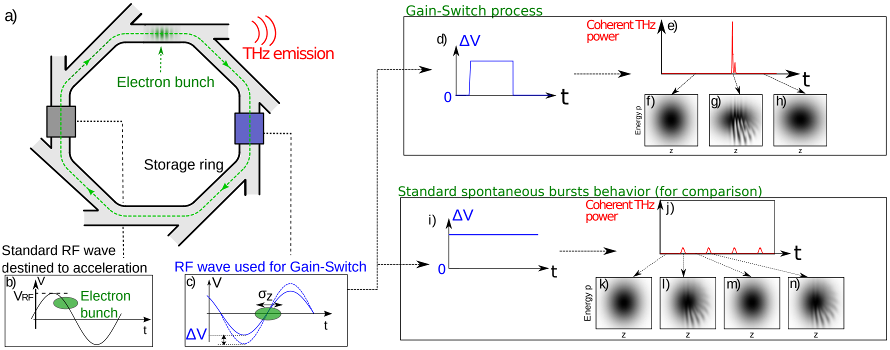
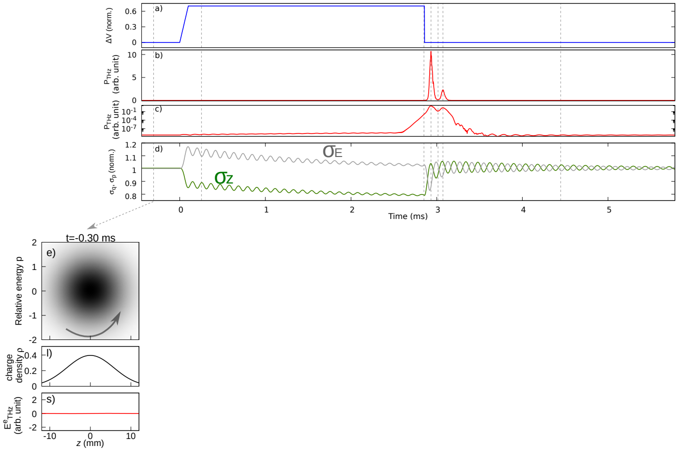


Principle in details

1. Init. cond. below therhold : stationnary quasi-gaussian distribution of the e-bunch



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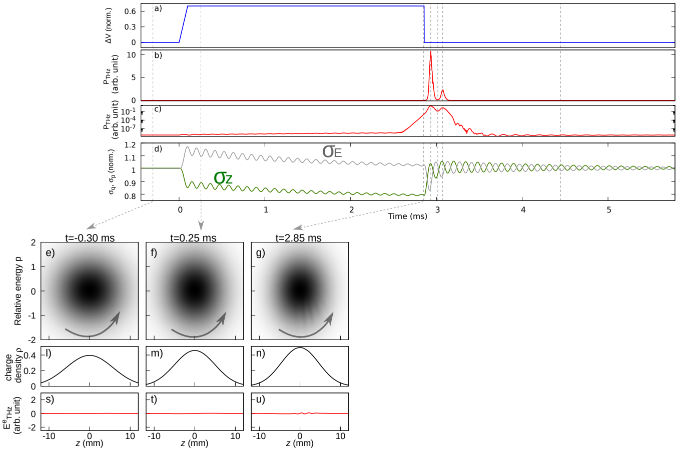

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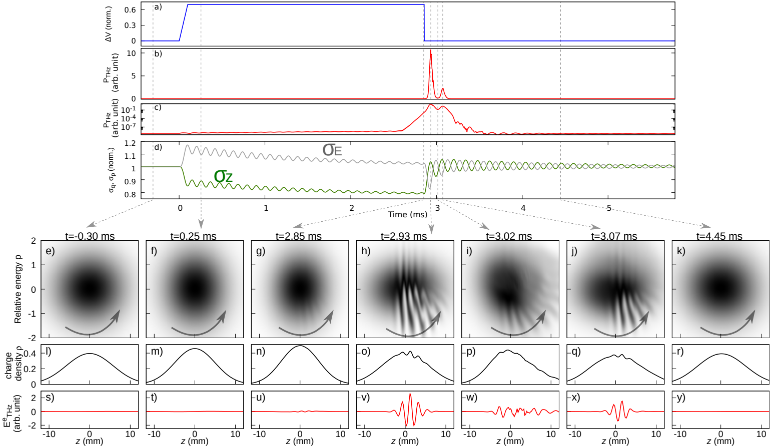
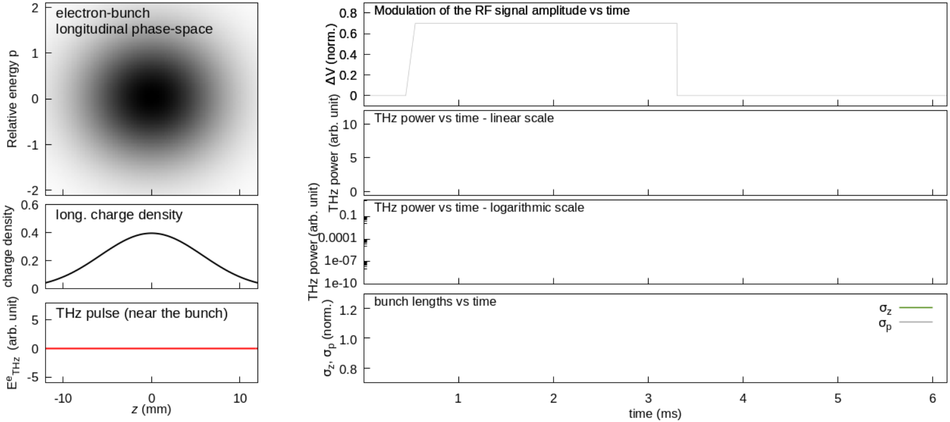
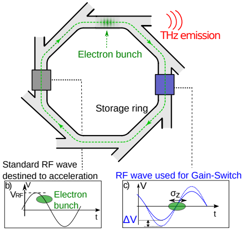
2. increase $\Delta V \Rightarrow \sigma_z$ decreases $\Rightarrow$ system above threshold $\Rightarrow$ apparition of micro-structures
3. sudden decrease of $\Delta V \Rightarrow$ temporary decrease of the energy-spread (due to the phase-space rotation at the synchrotron frequency) $\Rightarrow$ high gain for the initial micro-structures $\Rightarrow$ strong amplification $\Rightarrow$ strong THz burst



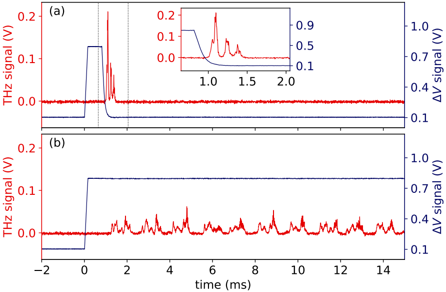
Video of the electron bunch dynamics



Exp. results



Results (for best parameters)



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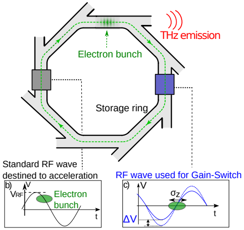
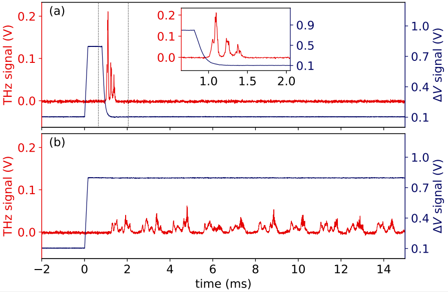
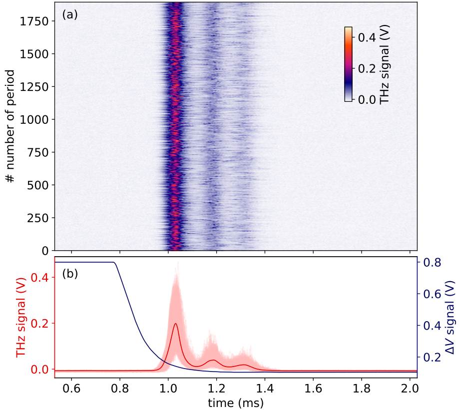


Results (for best parameters)

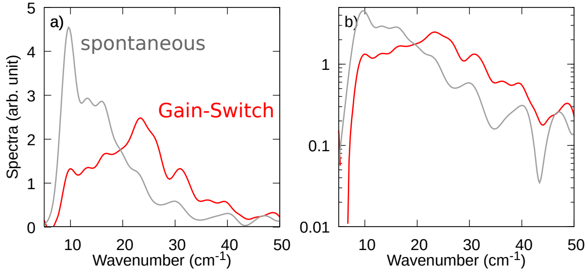


Repeatability



- Main peak amplitude fluctuations $\sim 20\%$ (RMS)
- Jitter $< 1\%$ (of the duration of the plateau)

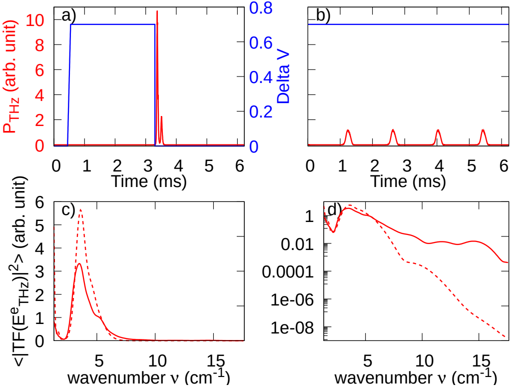
Exp. - Spectra from Fourier-transform interferometer



Broader THz spectrum with Gain-Switching ⇒ shorter micro-structures in the bunch

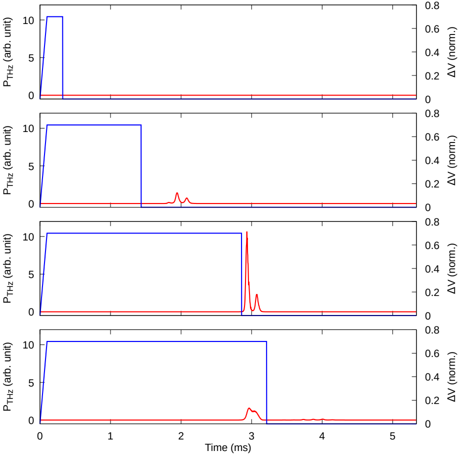
Conclusion - Gain-switching part

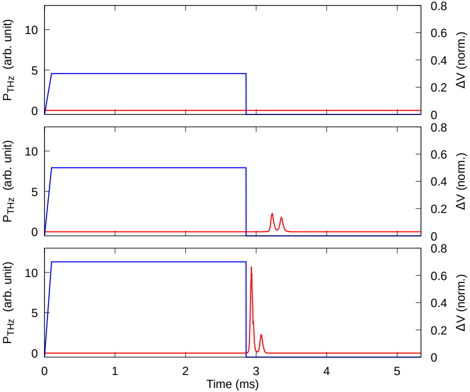
- Gains-Switch process - in analogy to laser systems
- based on a modulation of a RF-cavity signal
- due to a combined effect of **the appearance of micro-structures**, together with a **temporary increase of the microbunching instability gain** (due to a diminution of the bunch energy-spread)
- permit the emission of **a burst** of coherent THz synchrotron radiation with **a high amplitude** and **synchronized** with the modulation of the RF signal
  [C. Evain et. al., *Gain Switching of the Microbunching Instability to Produce Giant Bursts of Terahertz Coherent Synchrotron Radiation* to appear in PRL]
- More general conclusion : these two processes (control & Gain-Switching) show the possiblity to manipulate the e-bunch dynamics during the microbunching instability (via a RF signal amplitude modulation) and obtain a coherent THz emission with new characteristics
- Next step
  - Control : find methods to control at higher current
  - Gain Switch : periodic modulation


a)
b)
c)
d)
P_{THz} (arb. unit)
Delta V
Time (ms)
Time (ms)
<|TF(E^e_{THz})|^2> (arb. unit)
wavenumber ν (cm^{-1})
wavenumber ν (cm^{-1})

par :

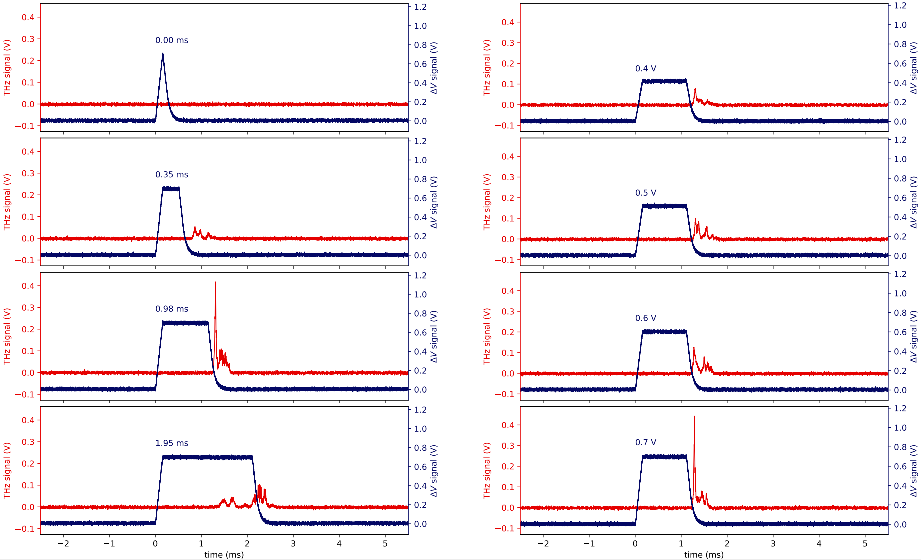
num. - THz signal vs modulation parameters





par :

Exp. - THz signal vs modulation parameters



Instability gain in function of the bunch dimensions and the Boussard criterion

Boussard criterion gives the following formula for the threshold current I_{th} for the microwave instability :

$$I_{th} \leq \frac{n}{Z} F \frac{E_0}{e} \eta \gamma \sigma_z \left(\frac{\sigma_p}{\gamma m c} \right)^2, \tag{1}$$

with $n = \omega/\omega_0$ (with $\omega_0 = 2\pi/T_0$ and T_0 the revolution period of the electrons in the storage ring), Z the impedance value (due - here - to the interaction of the electron with their radiation), η, γ the Lorentz factor, c the light velocity, F a constant depending on the electron distribution.

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pages to expect for this document.