Harmonic cavities studies and applications for SOLEIL upgrade: bunch lengthening, transient beam loading and instabilities

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Acknowledgements to N. Yamamoto (KEK), P. Marchand, R. Nagaoka and all SOLEIL colleagues …

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Introduction

In (most) 4th generation low emittance storage rings, harmonic cavities (also called Landau cavities) are critical components needed to reach design performances.

They are mainly used to lengthen the bunches which provide:

- Reduced intra-beam scattering (IBS)
- Increased Touscheck lifetime
- Reduced bunch spectral width
    - ➢ Reduced heating
    - ➢ Reduced overlap with the high frequency region of the impedance spectrum

Harmonic cavities also provide synchrotron tune spread:

- Within a bunch
- From bunch to bunch
    - ➢ Help to damp longitudinal (SB & MB) instabilities.
    - ➢ Can help to damp some transverse instabilities (if the head-tail mode number is > 0).

Introduction

But harmonic cavities (HC) have also some drawbacks:

- They can induce several instabilities.
  - The **DC Robinson instability**, which is a phase stability problem. Above a current threshold, the potential well produced by the beam loading voltage in the cavity begins to be unstable for the single particle motion (no oscillation).
  - The **AC Robinson instability**, which is defined as a longitudinal coupled-bunch instability driven by the fundamental cavity mode. So a special case of the usual HOM instability case.
  - The TMCI threshold (so at zero chromaticity) is reduced by HC in bunch lengthening mode.
- **Transient beam loading** (TBL) if the beam filling scheme is not symmetric. The TBL comes from the fact that the cavities interact with a variable current along the bunch train. This leads to a spread of the phases and voltages seen by the bunches along the train:
  - Bunch to bunch phase shift
  - Bunch length variation along the bunch train

Overview

- Difference between active/passive and normal/super conducting HC (in the beam dynamics point of view).
- How to compute beam loading equilibrium (Haïssinski vs tracking).
- Case study: a passive normal conducting HC (ALS-U) and a passive super conducting HC (SOLEIL-U).
- Present results for SOLEIL-U with different filling patterns, 3rd harmonic vs 4th harmonic.
- The transient beam loading (TBL) problem.

(active or perfect) Harmonic cavity

The total voltage given by an RF system with a m^th harmonic cavity can be expressed as:

$$V_{tot}(t) = V_1\cos(\omega_{RF}t + \phi_1) + V_2\cos(m\omega_{RF}t + \phi_2)$$

Voltage and phase of the main cavity

Voltage and phase of the harmonic cavity

Where the following condition is imposed to insure energy balance: $V_{tot}(0) = \frac{U_{loss}}{e}$

Losses per turn

The RF system is usually operated near the "flat potential conditions":

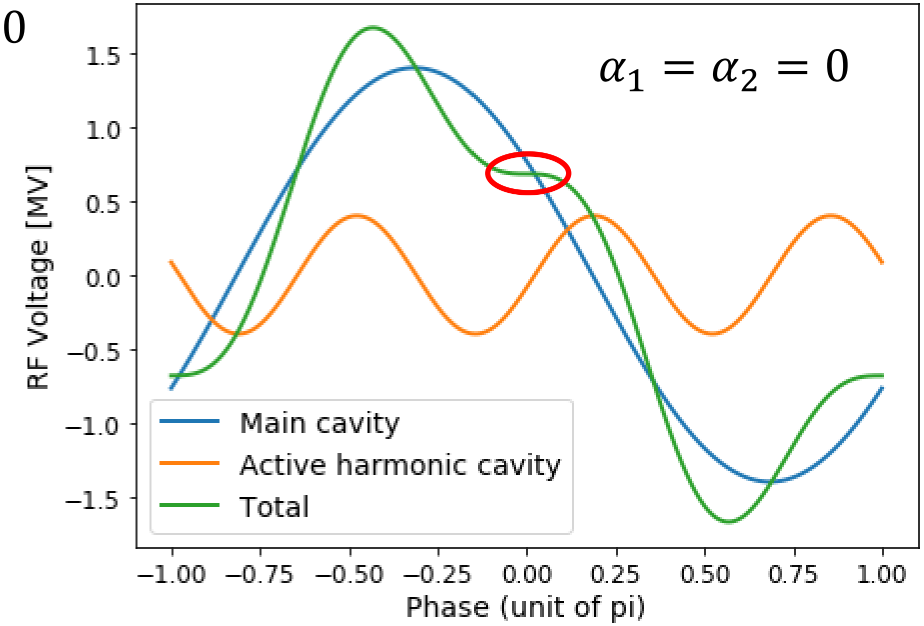
$$\frac{dV_{tot}}{dt}(0) = \alpha_1 \approx 0 \qquad \frac{d^2V_{tot}}{dt^2}(0) = \alpha_2 \approx 0$$

Which gives the following conditions:

$$\cos(\phi_1) = \frac{m^2}{m^2-1}\frac{U_{loss}}{eV_1}$$

$$\tan(\phi_2) = \frac{(V_1\omega_{RF}\sin(\phi_1) - \alpha_1)\,m}{V_1\omega_{RF}\cos(\phi_1)}$$

$$V_2 = -\frac{V_1\cos(\phi_1)}{m^2\cos(\phi_2)}$$



(passive) Harmonic cavity

For a passive harmonic cavity, the voltage and the phase of the harmonic cavity can not be set independently. The harmonic voltage is given by:

Form factor (depend on bunch profile)

$$V(t) = -2I_0 R_s \, \mathrm{F} \cos(\psi) \cos(m\omega_{RF} t + \psi \; + \Phi)$$

Beam current

Cavity shunt impedance

Where ψ is the tuning angle, which is linked to the resonance angular frequency ω_r of the cavity by:

$$\tan(\psi) = Q \left(\frac{\omega_r}{m\omega_{RF}} - \frac{m\omega_{RF}}{\omega_r} \right)$$

Cavity quality factor

For a chosen beam current I_0 and shunt impedance R_s, conditions to get the “flat potential” are very similar to the active case:

$$\tan(\psi) = \frac{(V_1 \omega_{RF} \sin(\phi_1) - \alpha_1)\, m}{V_1 \omega_{RF} \cos(\phi_1)}$$

$$\cos(\phi_1) = \frac{m^2}{m^2 - 1} \frac{U_{loss}}{eV_1}$$

$$V_2 = -\frac{V_1 \cos(\phi_1)}{m^2 \cos(\psi)^2} = -2I_0 R_s$$

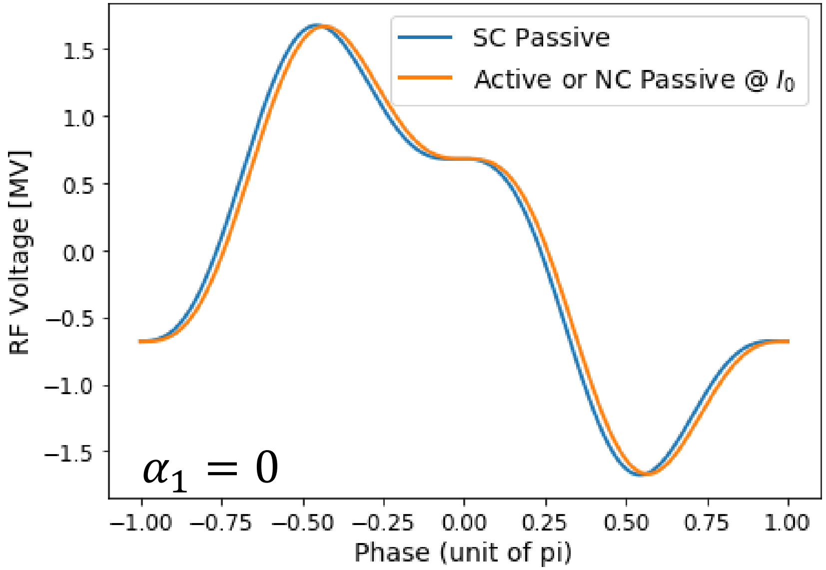
But if I_0 and R_s are already fixed, only 2 degrees of freedom are left with ψ and ϕ_1 so it is not possible to achieve “flat potential” any more.

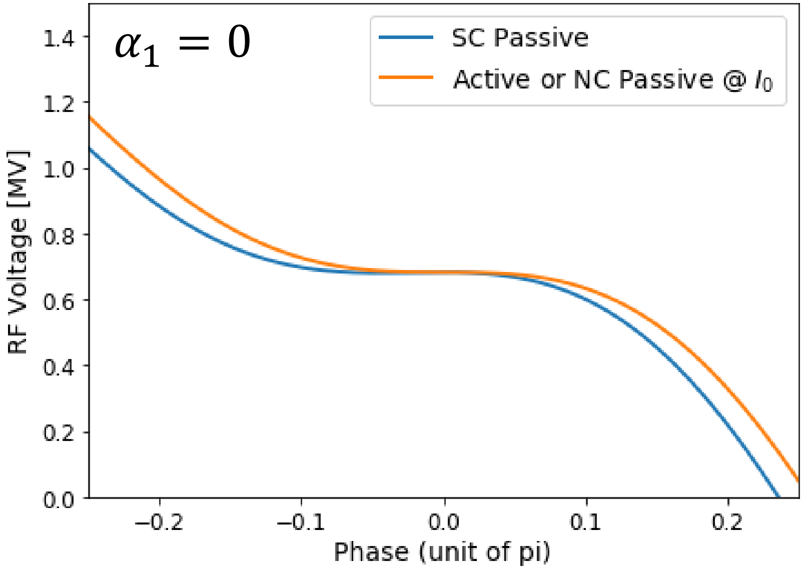
$$V_{tot}(0) = \frac{U_{loss}}{e} \qquad \frac{dV_{tot}}{dt}(0) = \alpha_1 \approx 0 \qquad \xcancel{\frac{d^2 V_{tot}}{dt^2}(0) = \alpha_2 \approx 0}$$

Normal/Super conducting passive HC

For a normal conducting (NC) passive harmonic cavity, you can design the system ($R_s \approx M\Omega$) in such a way to achieve “flat potential” conditions for given current value I_0. For all other currents, the cavity tuning needs to change to get the correct voltage in the harmonic cavity which also change the phase, so you can not cancel $\frac{d^2V_{tot}}{dt^2}$.

For a super conducting (SC) passive harmonic cavity, the shunt impedance R_s is very high, typically $R_s \approx G\Omega$, so the current needed to be at “flat potential” condition is very low. In practice, you can never have $\frac{d^2V_{tot}}{dt^2} = 0$.





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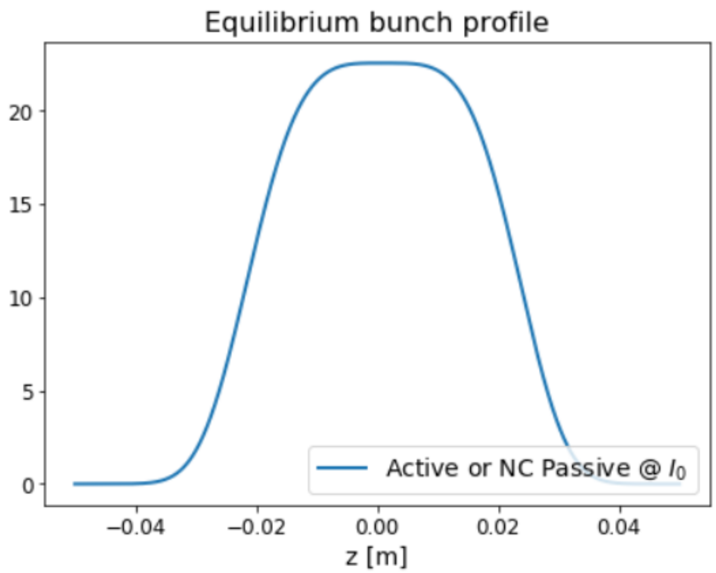

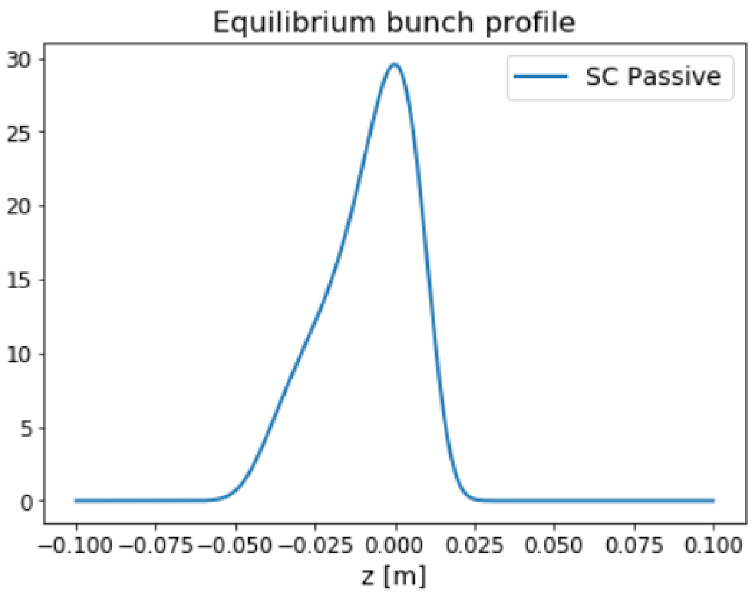

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“Analytic” calculation of bunch profile

It is possible to compute the bunch profile from the total voltage of the RF system by solving a system similar to the Haïssinski equation[1]:

- Define a scaled potential which depends on the bunch profile via F and Φ:

$$u(t) \propto \int^{t} (eV_{tot}(t';F,\Phi) - U_0)dt'$$

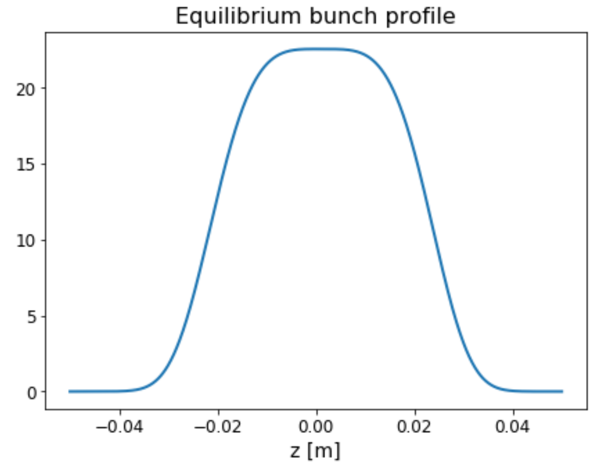
- The bunch profile is then given by $\rho_0(t) = \dfrac{e^{-u(t;F,\Phi)}}{\int e^{-u(t\prime;F,\Phi)}dt'}$

FT of the bunch profile taken at $m\omega_{RF}$

System of equation to solve numerically to find F, Φ and ϕ_1

$$\begin{cases} \tilde{\rho}_0(m\omega_{RF}) = Fe^{i\Phi} = \int e^{im\omega_{RF}t}\,\rho_0(z)dz = \dfrac{\int e^{im\omega_{RF}t}e^{-u(t;F,\Phi)}}{\int e^{-u(t\prime;F,\Phi)}dt'} \\ V_{tot}(0) = \dfrac{U_{loss}}{e} \end{cases}$$

For a given R_s and ψ, you get F, Φ and ϕ_1 which allows you to compute the bunch profile. **Finding a solution does not say anything about its stability. But if no solution exists, the beam can not be stable.**


Equilibrium bunch profile

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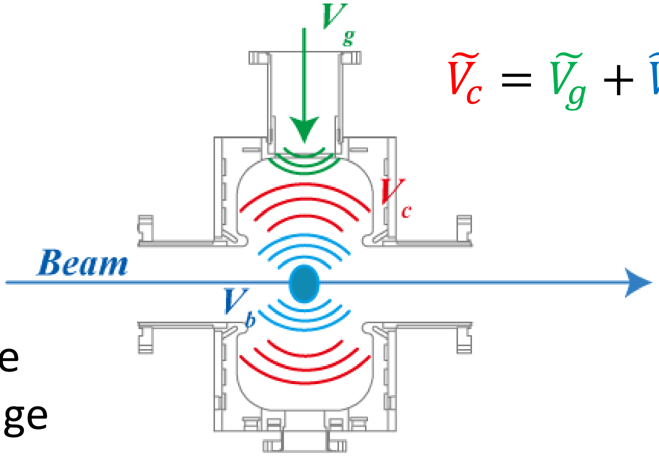
[1] Venturini, M. (2018). Passive higher-harmonic rf cavities with general settings and multibunch instabilities in electron storage rings. *Physical Review Accelerators and Beams*, *21*(11), 114404.

In macro-particle tracking

The usual way to include RF systems in macro-particle tracking code is just a sum of cosine (or sine) like:

$$\Delta_{RF} = \sum_{n} \frac{eV_n}{E_0} \cos(m_n \omega_{RF} t + \phi_n)$$

But this approach can not simulate instabilities generated by the RF system or the transient beam loading. Instead, the total cavity voltage $\widetilde{V_c}$ is decomposed in two components, the generator voltage $\widetilde{V_g}$ and the beam induced voltage $\widetilde{V_b}$.



$$\widetilde{V_c} = \widetilde{V_g} + \widetilde{V_b}$$

When a charged particle goes through the RF cavity, it induces a voltage $\widetilde{V_0}$:

$$\widetilde{V_0} = -2qk_l$$

Particle charge

Cavity loss factor

The voltage induced by the different particles crossing the cavity between time *t* and time *t*+Δ*t* is added to the voltage $\widetilde{V_b}$ already present in the cavity at time *t*:

$$\widetilde{V_b}(t + \Delta t) = \widetilde{V_b}(t) e^{-\frac{\Delta t}{\tau}} e^{j\delta \Delta t} + \widetilde{V_0}$$

Cavity filling time

Cavity phase slippage

So the energy change of a particle is given by[1]:

$$\Delta_{RF} = \sum_{n} \frac{e}{E_0} \left[V_{g,n} \cos\left(m_n \omega_{RF} t + \phi_{g,n}\right) + Re\left[\widetilde{V_b}\right] - qk_l \right]$$

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[1] Yamamoto, N., Gamelin, A., & Nagaoka, R. (2019). Investigation of Longitudinal Beam Dynamics With Harmonic Cavities by Using the Code Mbtrack. *IPAC'19*.

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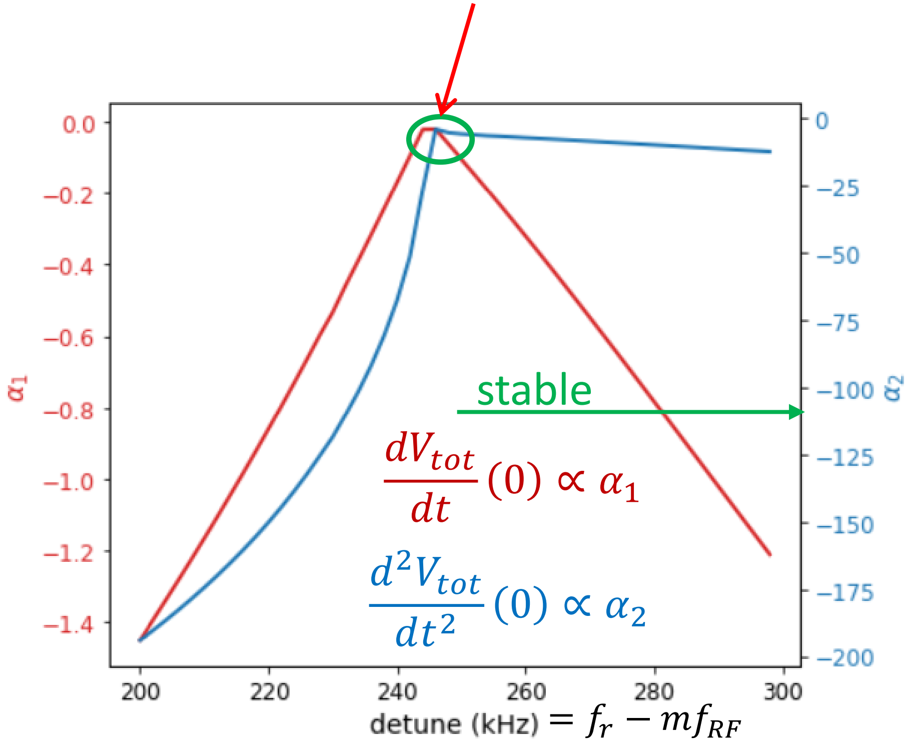
NC passive harmonic cavity

ALS-U case @ $\mathbf{I} = \boldsymbol{I_0} = 500$ mA

“Flat potential” conditions for 245 kHz

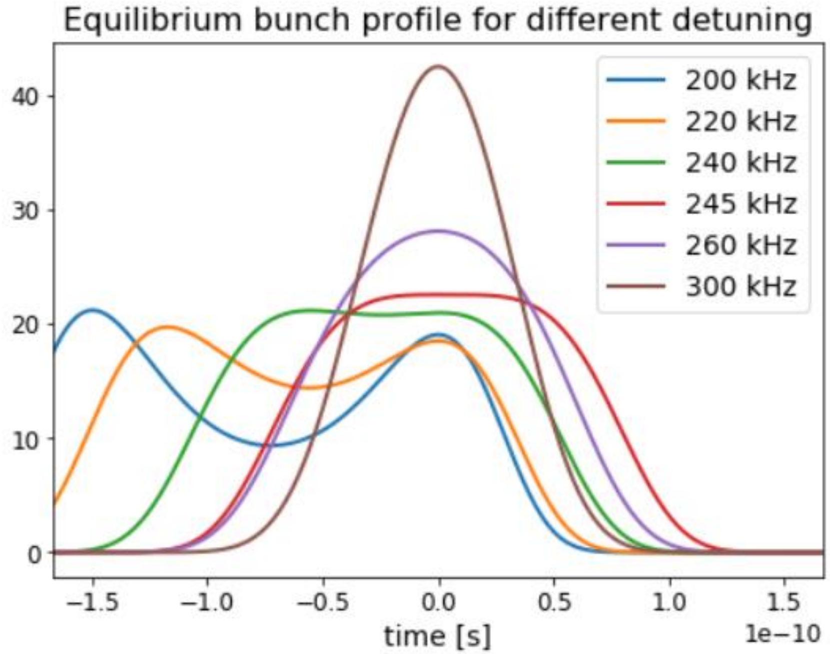
$$\alpha_1 \approx \alpha_2 \approx 0$$



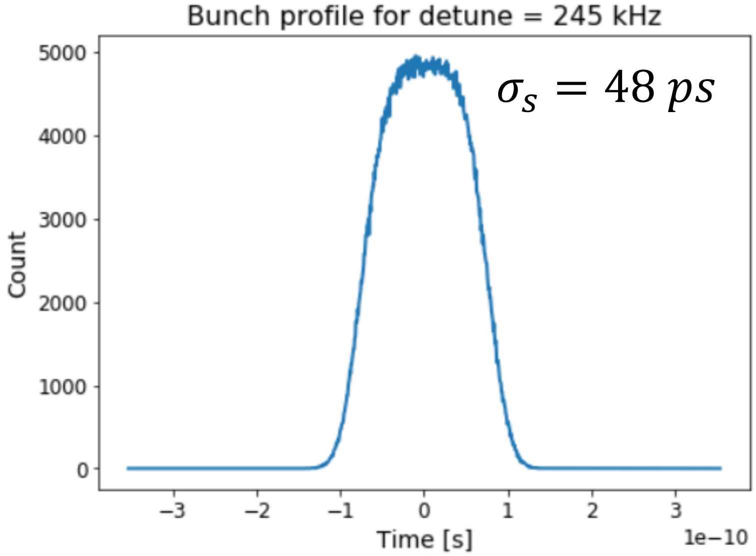
$$\frac{dV_{tot}}{dt}(0) \propto \alpha_1$$

$$\frac{d^2V_{tot}}{dt^2}(0) \propto \alpha_2$$

Equilibrium bunch profile for different detuning



Bunch profile for detune = 245 kHz



$$\sigma_s = 48\,ps$$

Simulation parameters[1]:

Main cavity:

- $V_{RF} = 0{,}6\ MV$

Passive harmonic cavity:

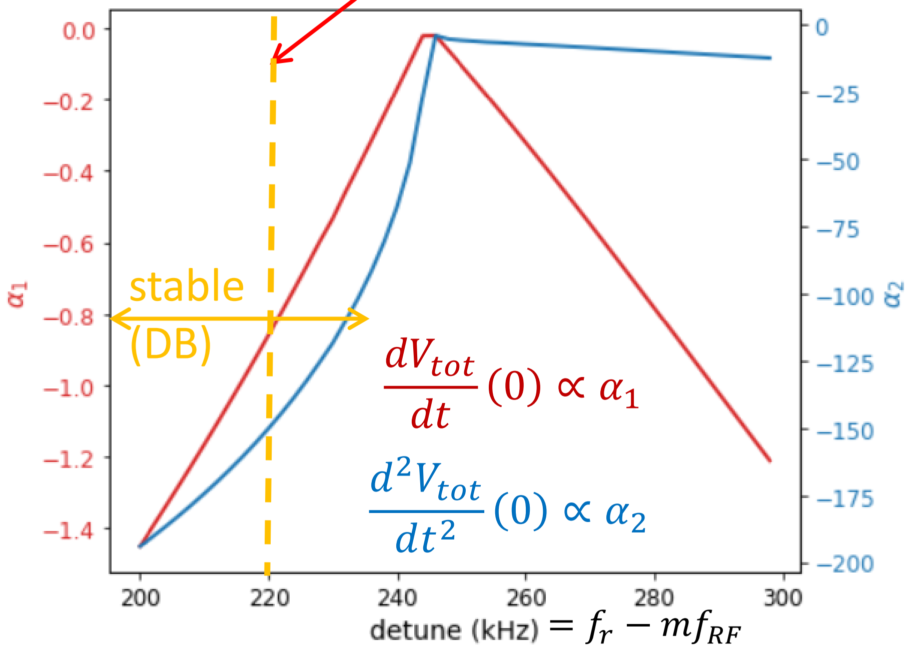
- $m = 3$
- $R_s = 1{,}35 \times 10^6\ \Omega$
- $Q_0 = Q_L = 20\ 000$

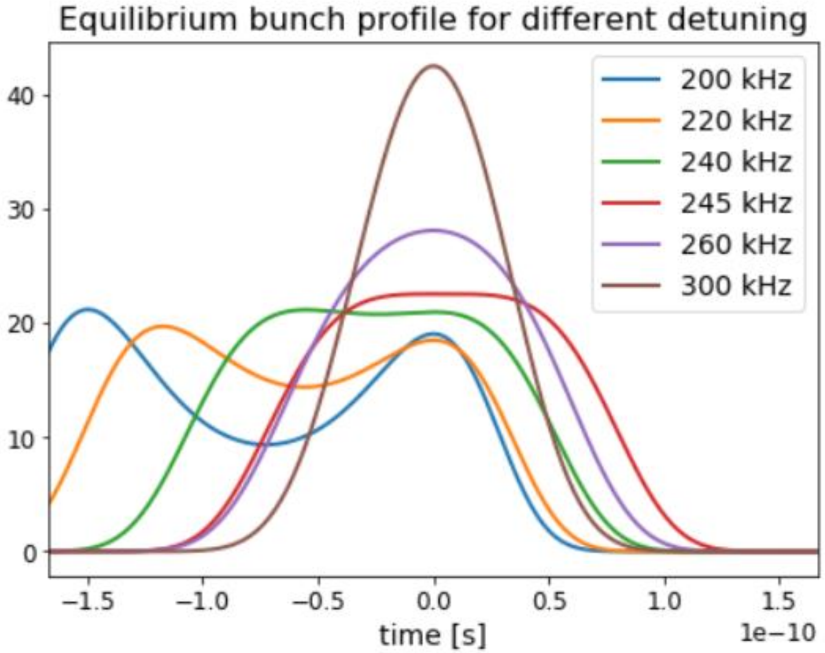
Parameters for ALS-U from: [1] Venturini, M. (2018). Passive higher-harmonic rf cavities with general settings and multibunch instabilities in electron storage rings. *Physical Review Accelerators and Beams*, *21*(11), 114404.

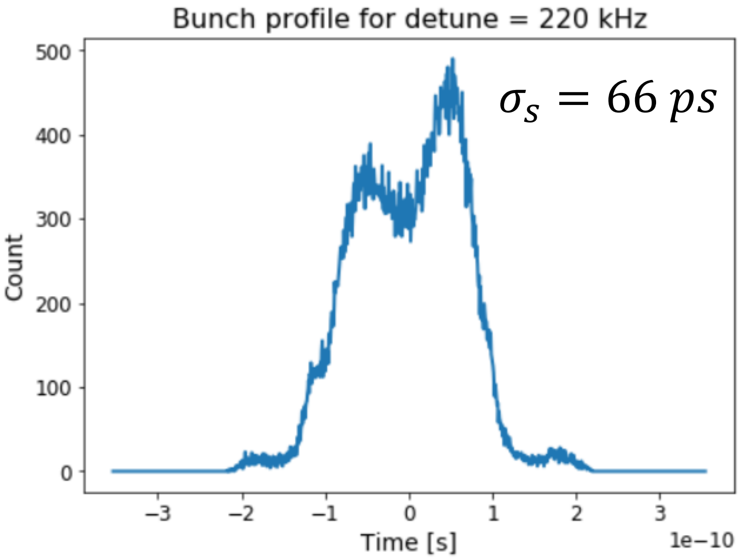
NC passive harmonic cavity

ALS-U case @ $\mathrm{I} = I_0 = 500$ mA

If the cavity is tuned past the flat potential condition, you get “double bump” profile.







NC passive harmonic cavity

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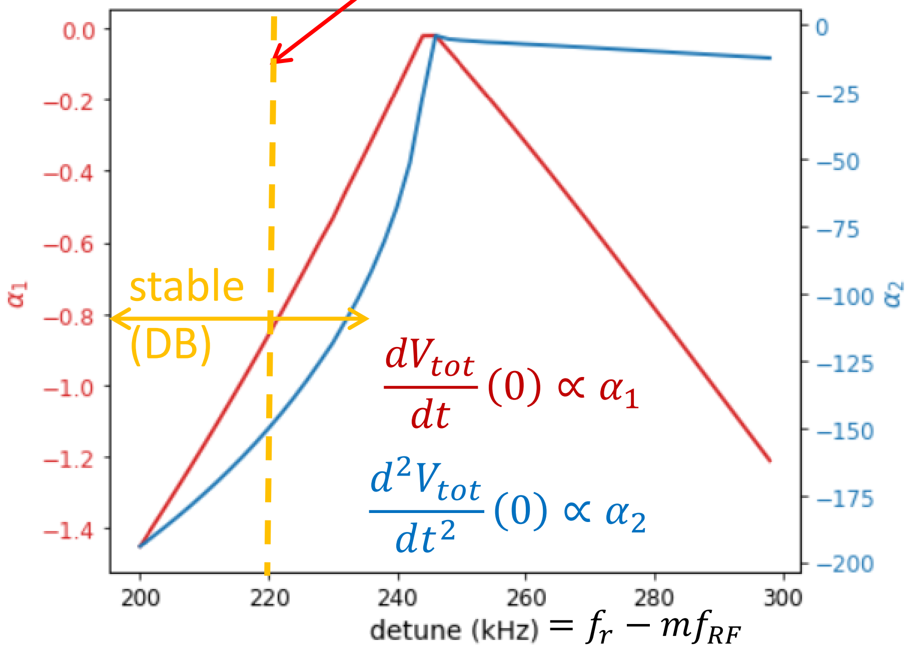
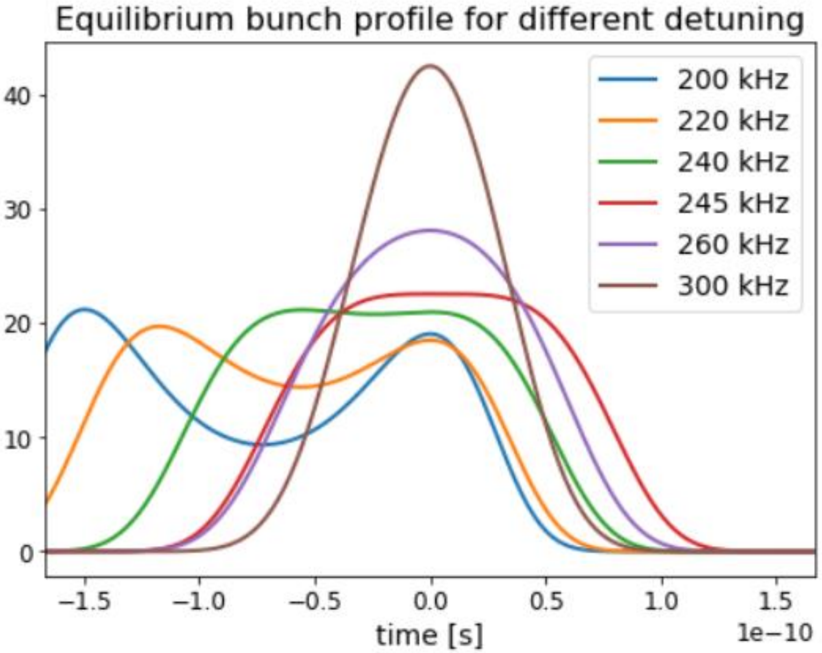
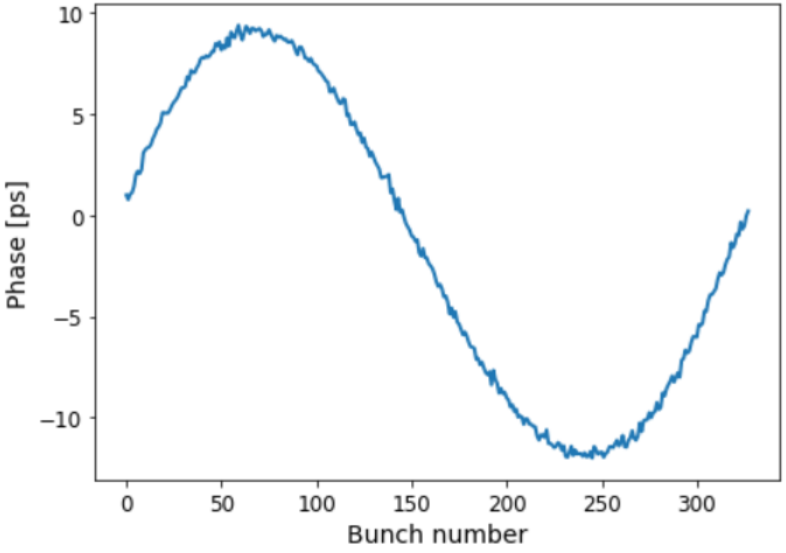




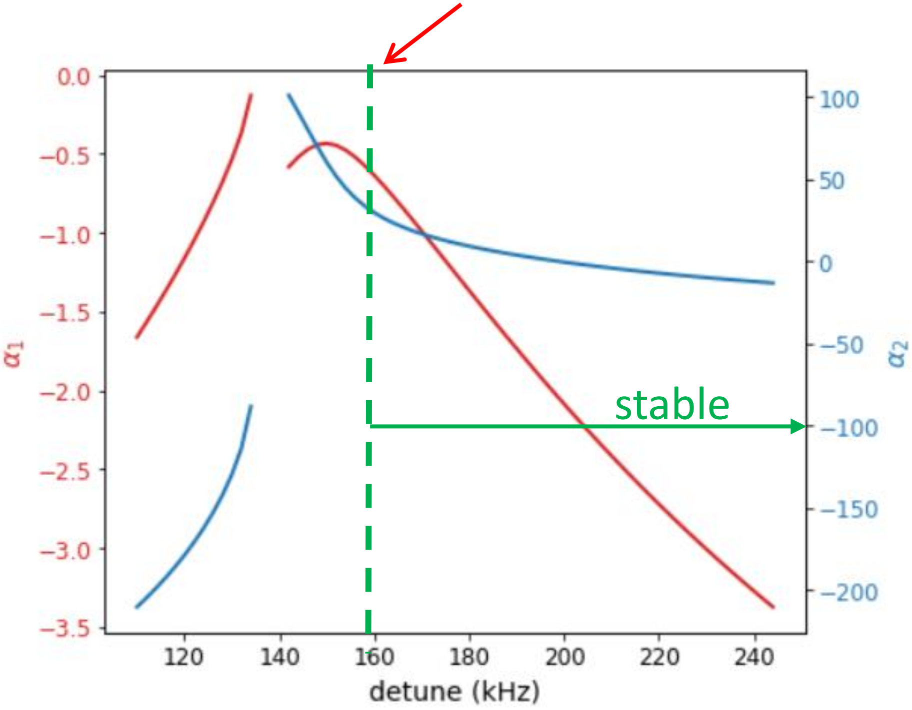


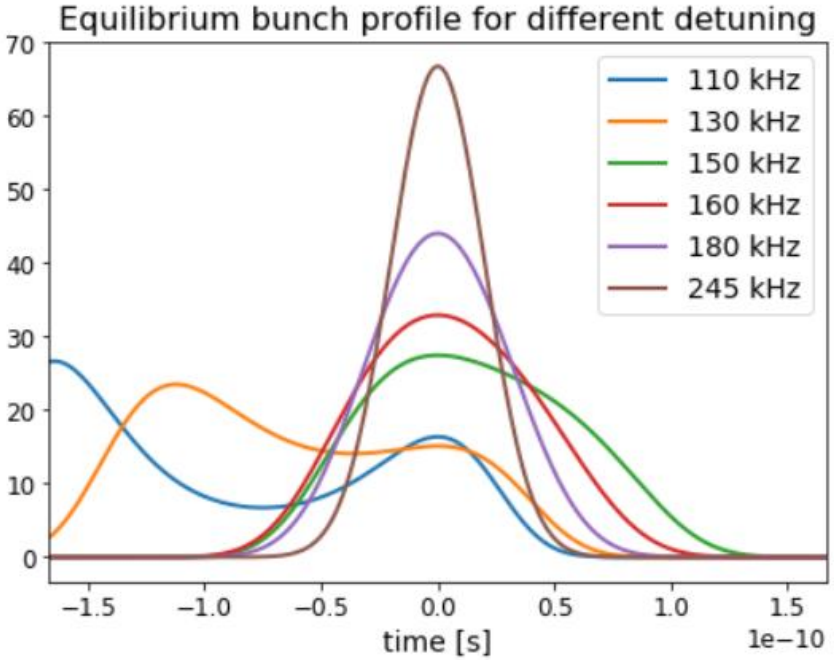
Coupled bunch motion starts to appear as the detuning decreases.

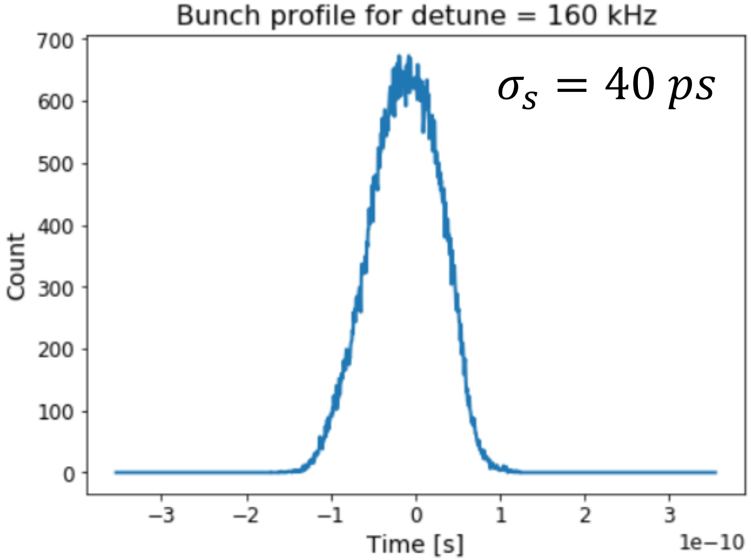
NC passive harmonic cavity

ALS-U case @ $\mathrm{I} = 300$ mA
$I_0 = 500$ mA

Can not reach “flat potential”, $\alpha_1 \neq 0$



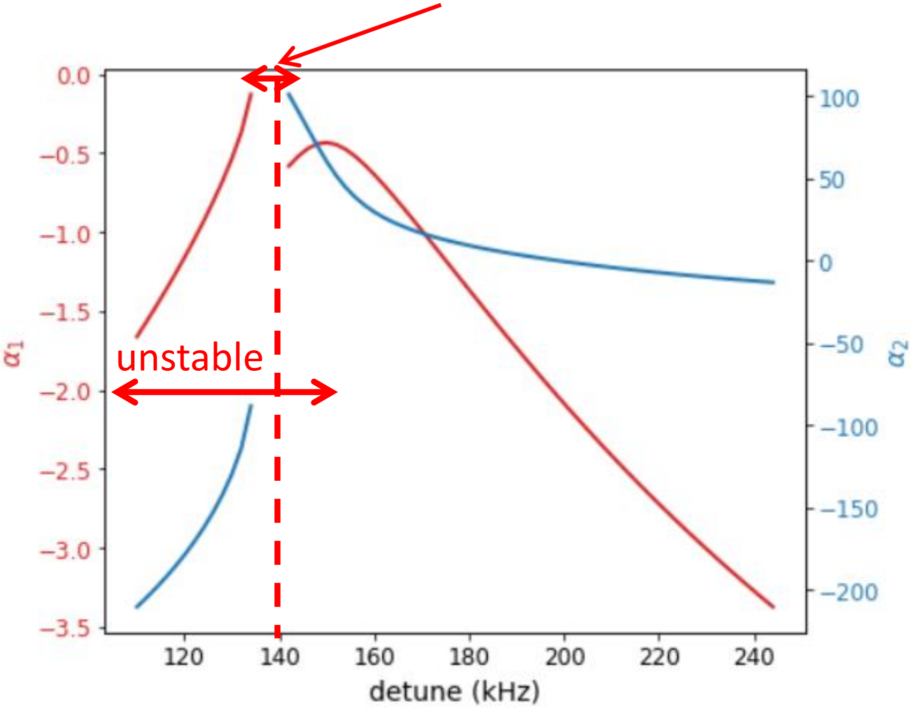




NC passive harmonic cavity

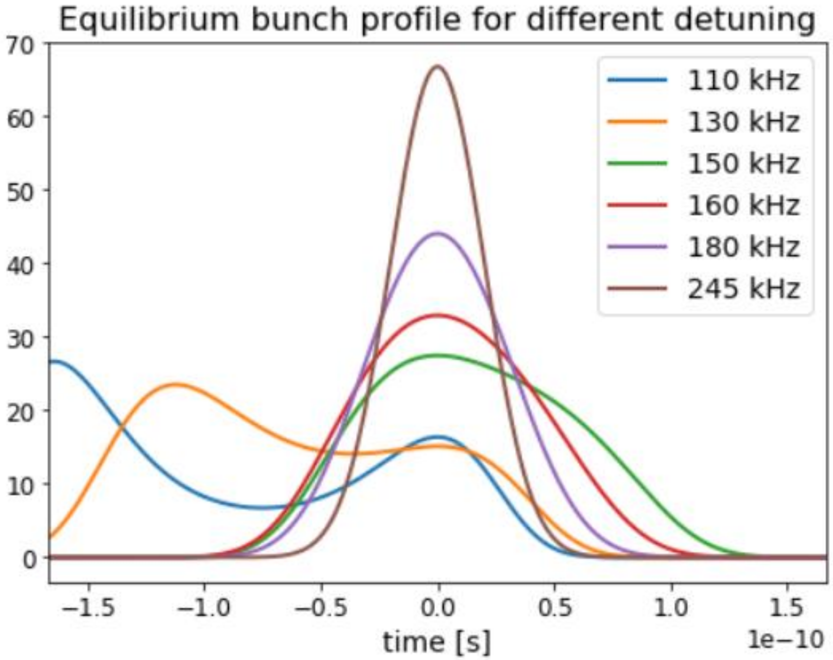
ALS-U case @ $\mathbf{I} = 300$ mA
$I_0 = 500$ mA

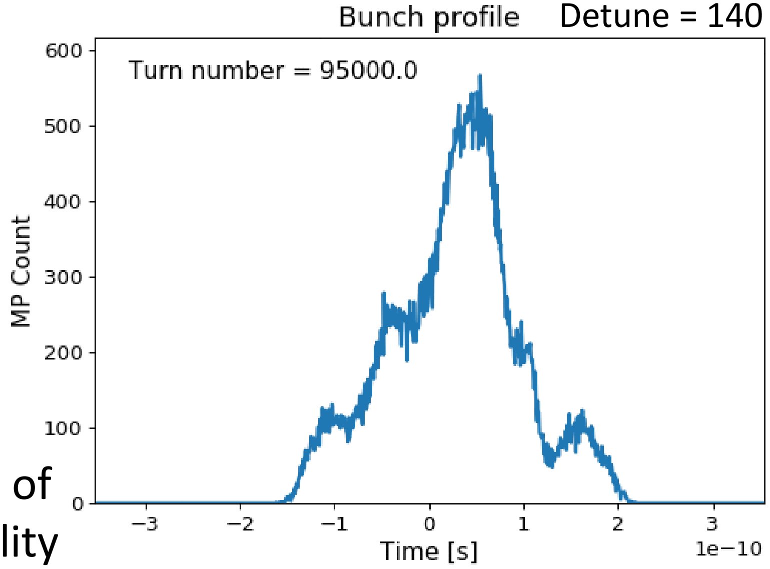
No solution for the Haïssinski solver.



Oscillations of bunch profile with a mix of dipole mode, quadripolar mode, …

Coupled bunch oscillations of bunch center of mass (dipole mode) => AC Robinson instability

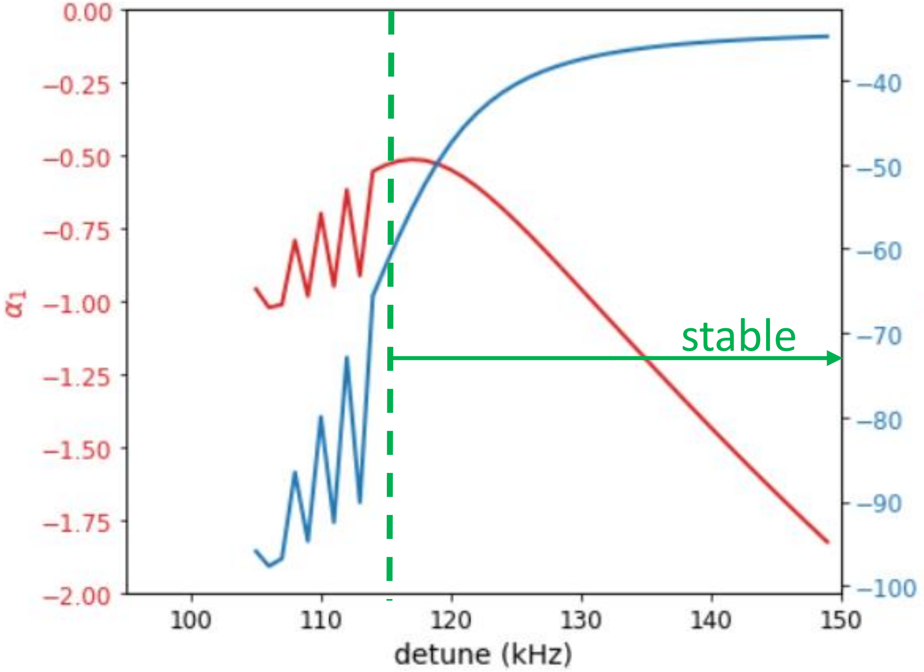




SC passive harmonic cavity

SOLEIL Upgrade case @ $\mathbf{I} = 500$ mA

SC HC so can not reach "flat potential", $\alpha_1 \neq 0$



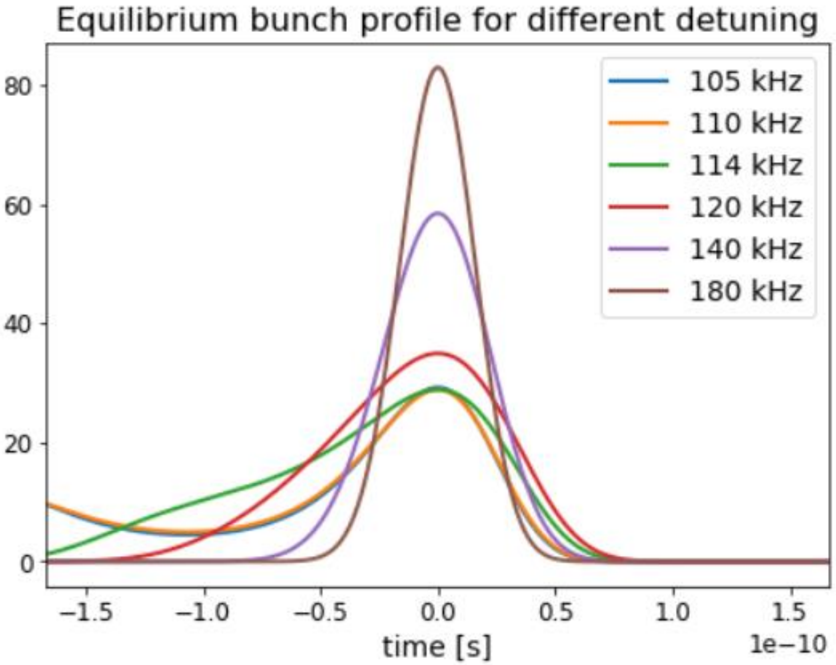
Simulation parameters:

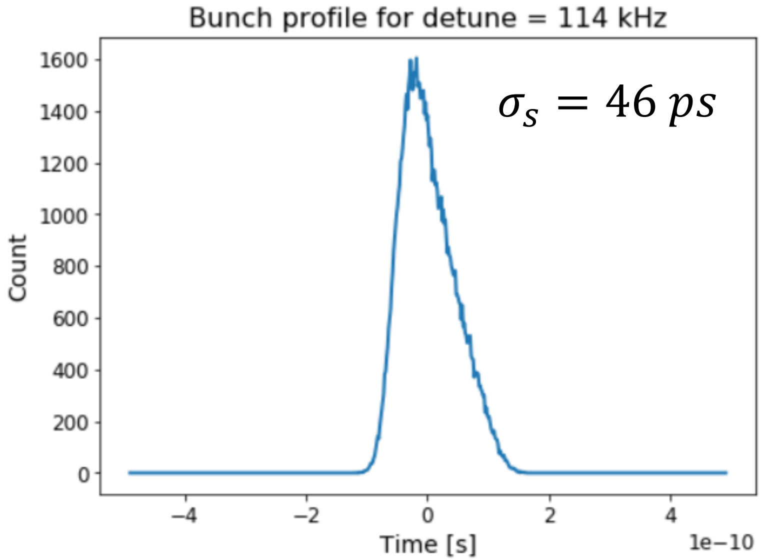
Main cavity (4 ESRF-EBS type):

- $R_s = 19{,}6\ M\Omega$
- $Q_0 = 34\ 000$
- $Q_L = 6\ 000$
- $V_{RF} = 1{,}4\ MV$

Passive harmonic cavity (2 Super3HC type):

- $m = 3$
- $R_s = 90 \times 10^8\ \Omega$
- $Q_0 = Q_L = 10^8$



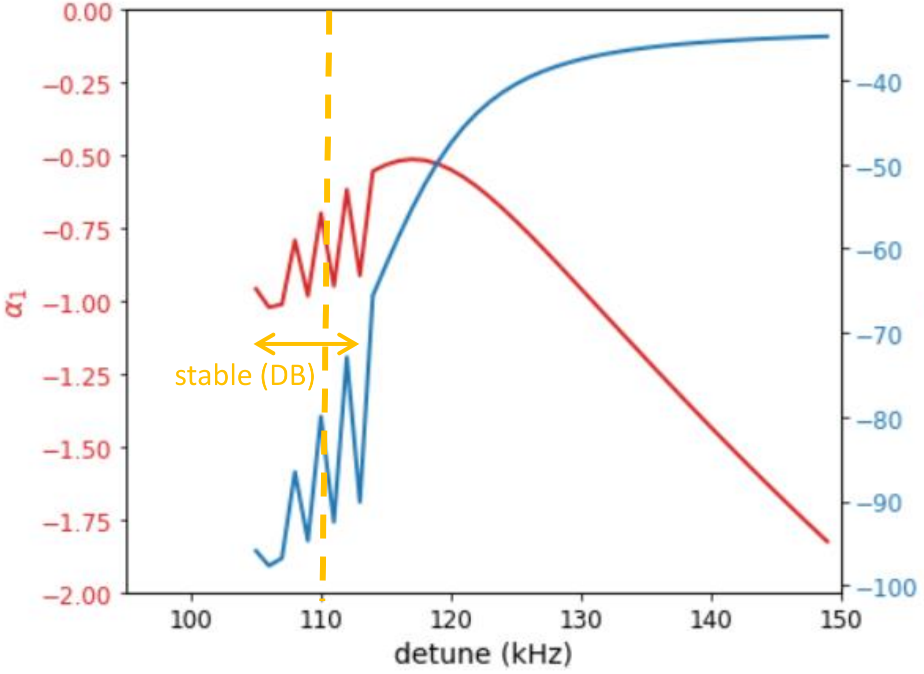


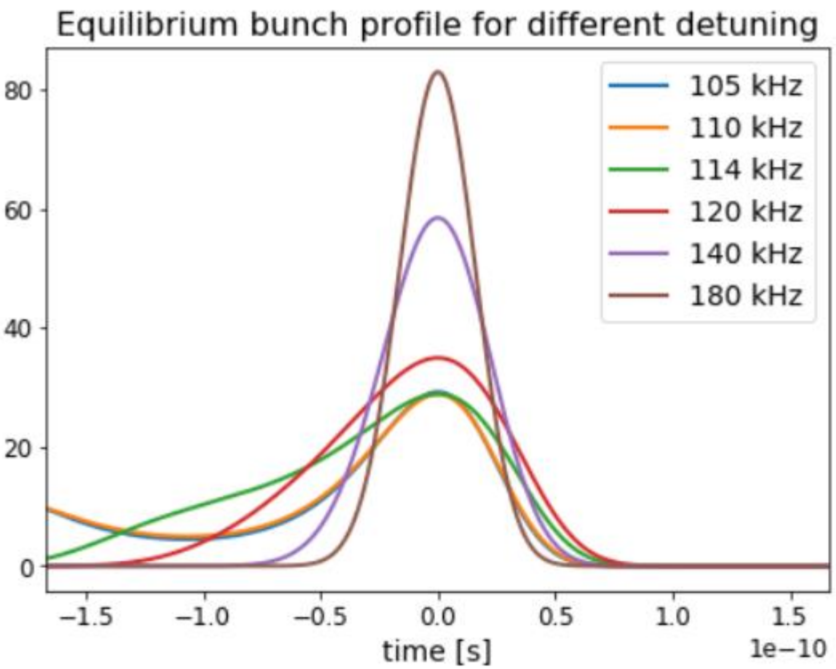
$\sigma_s = 46\ ps$

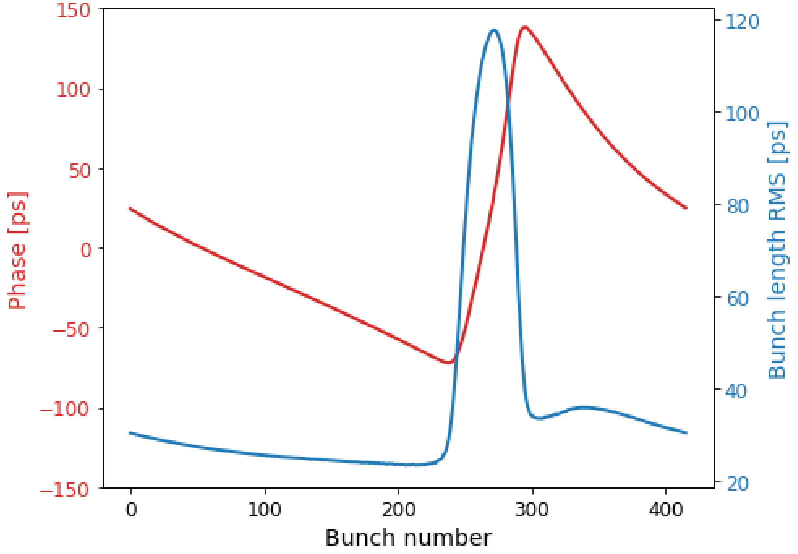
SC passive harmonic cavity

SOLEIL Upgrade case @ $\mathrm{I} = 500$ mA

“Double bump” profile on some of the bunches and strong coupled bunch motion







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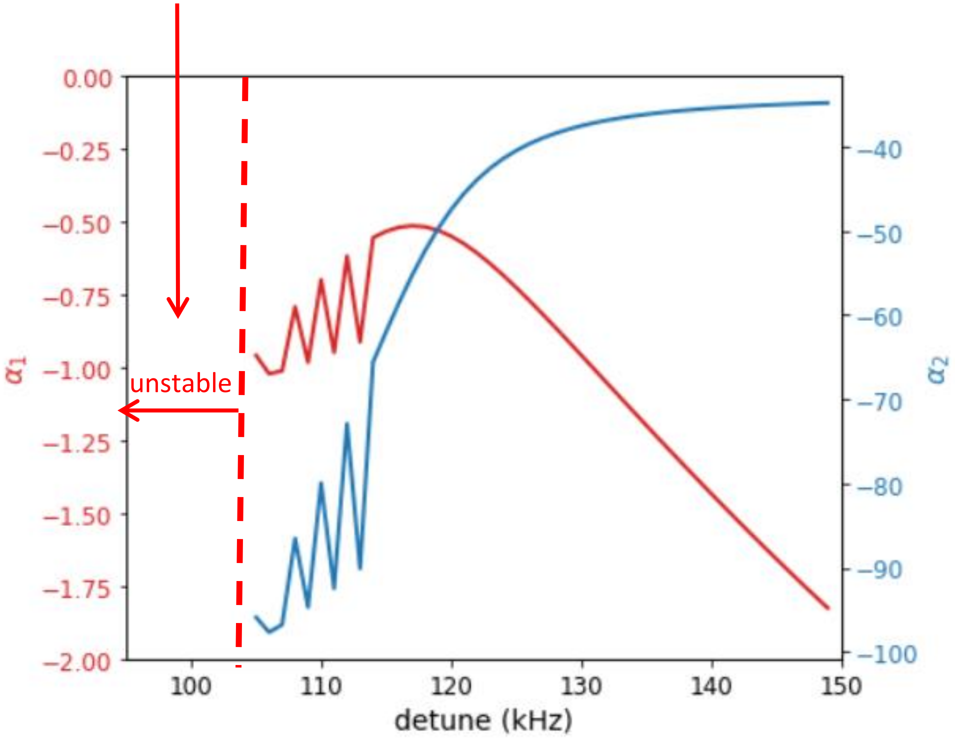

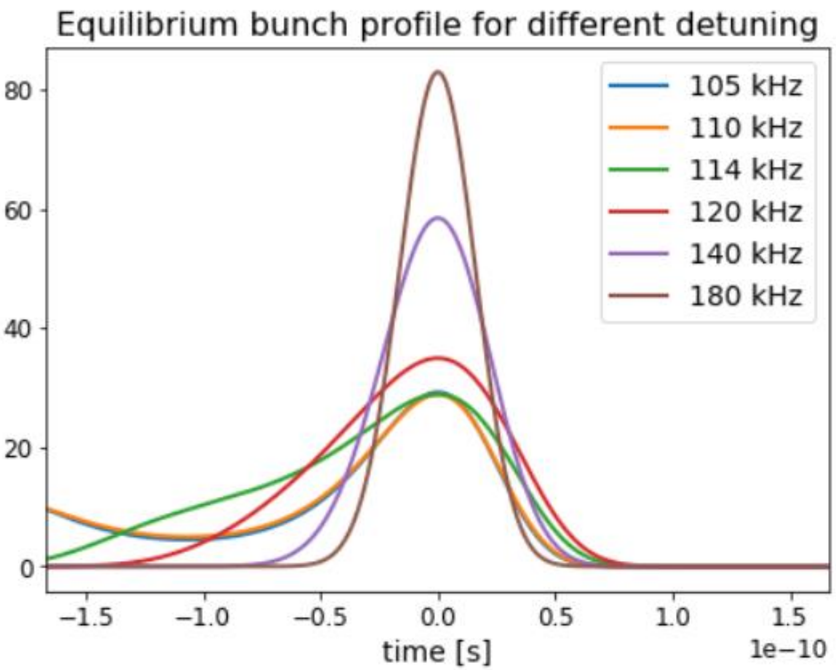

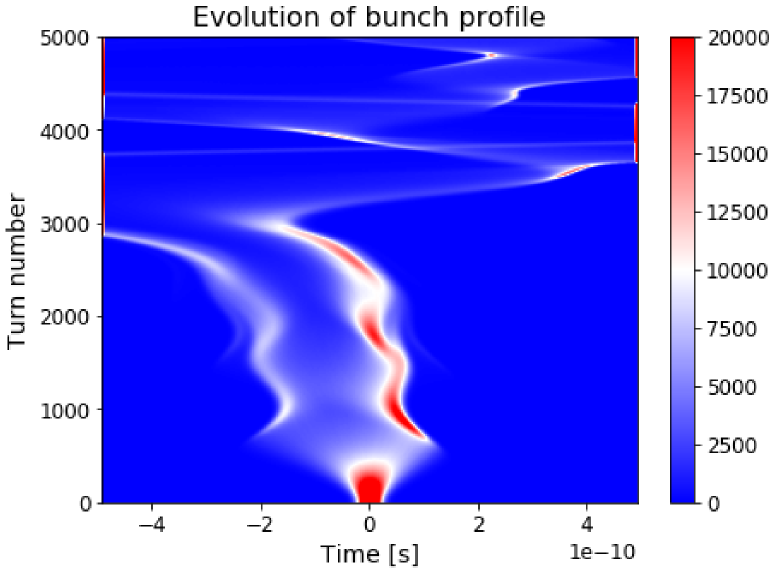

Fast loss of all bunches (oscillations of bunch profile with a mix of modes), dipole coupled bunch motion => AC Robinson instability

Some comments and conclusions about the case study

Depending on the parameters and on the cavity tuning, there are 3 distinct regimes:

- The bunch lengthening regime which starts from detune = $+\infty$ to the flat potential (or to the minimum of $\alpha_1 = \frac{dV_{tot}}{dt}$ if FP can not be reached).
- The double bump (DB) regime which starts after the maximum of α_1. But this regime is not always present, sometimes it goes directly to AC Robinson. I explain this stable state regime as the start of the coupled bunch instability which is stabilized by the bunch-to-bunch frequency spread induced by the phase shift.
- The AC Robinson regime where the center of mass of all bunches oscillates in phase and lead to beam loss. The different bunches oscillate in their potential which leads to the apparition of the mix of bunch profile modes.

Comments on methods:

- Good agreement between tracking and analytical calculation when the beam is stable.
- If it seems there is no solution of the equation system for the equilibrium bunch profile, it is a strong hint of an instability at that point.

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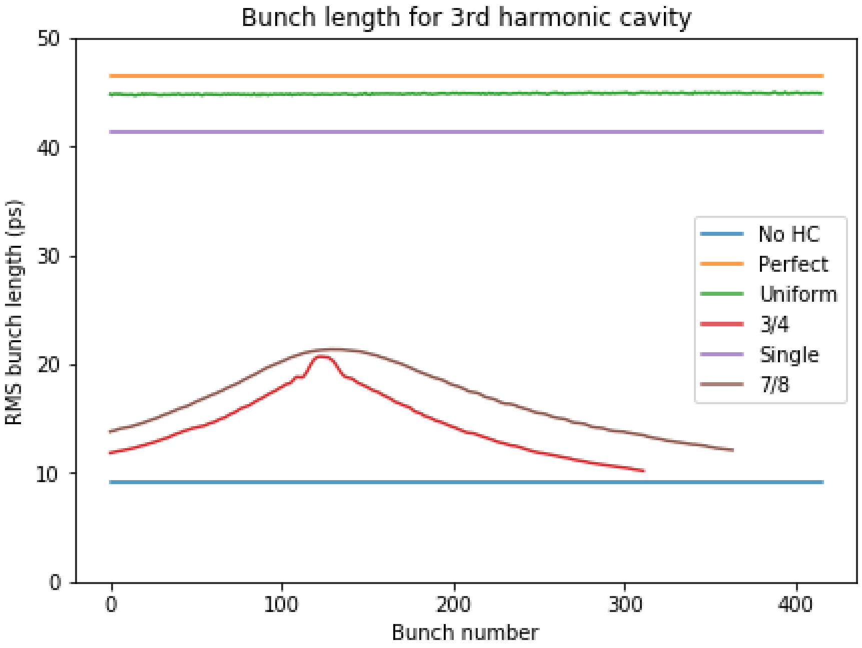
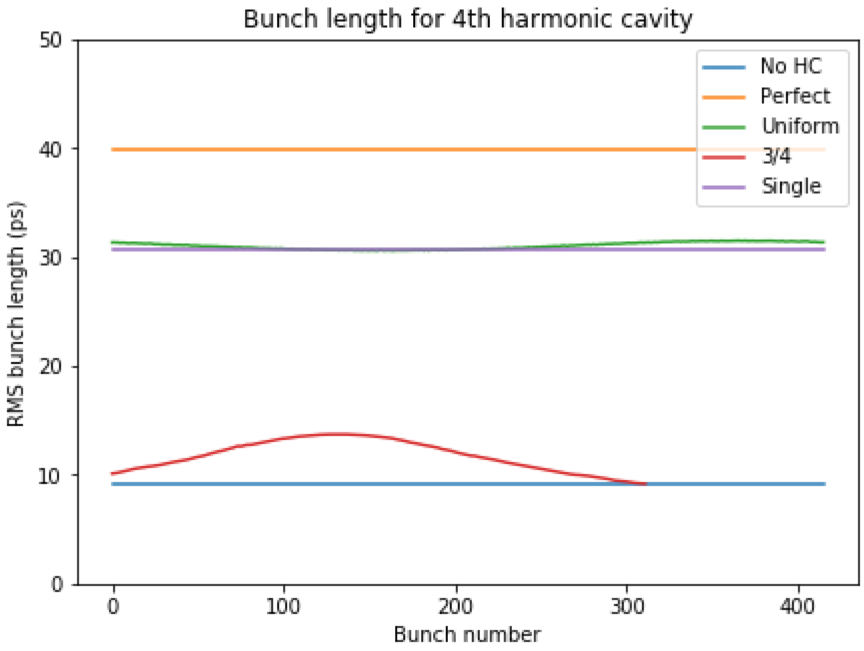
Results for SOLEIL-U

$$V_1 = 1{,}4\ MV$$

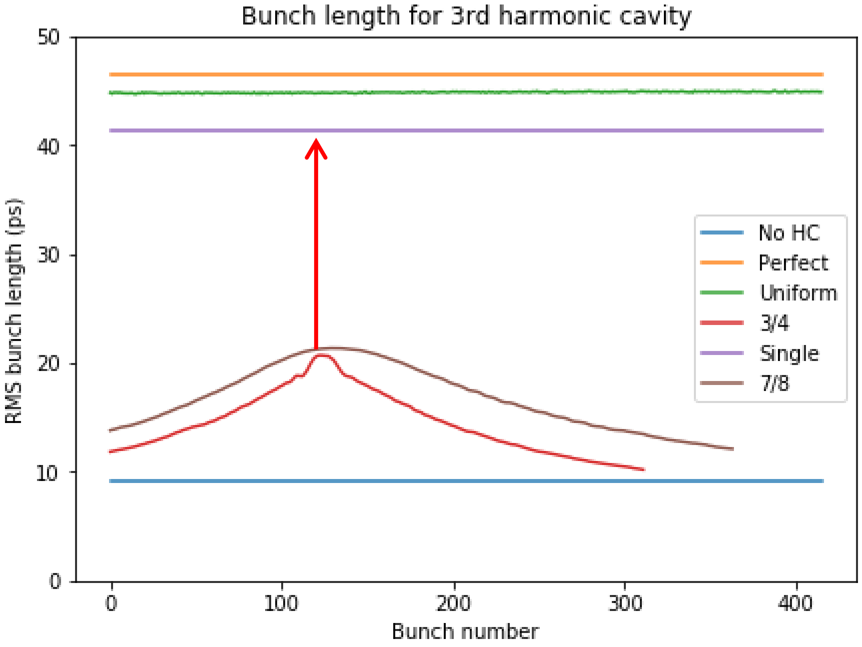


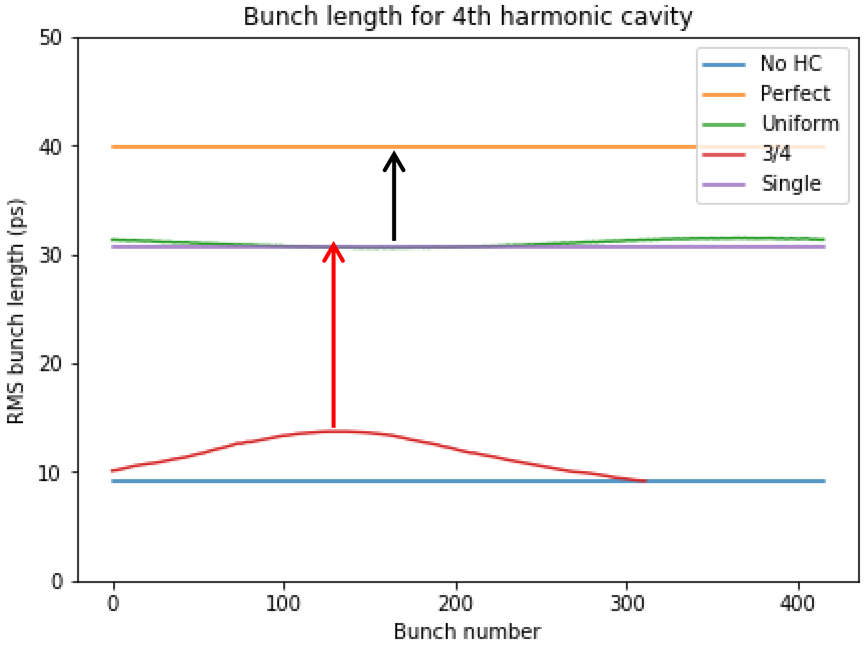


- No HC => natural bunch length σ_{s0}
- Perfect => cosine voltage without impedance
- Uniform => uniform fill and 500 mA
- ¾ => ¾ fill and 450 mA
- Single => single bunch and 20 mA
- 7/8 => 7/8 fill and 450 mA

Results for SOLEIL-U

$$V_1 = 1{,}4\ MV$$


Bunch length for 3rd harmonic cavity


Bunch length for 4th harmonic cavity

A few remarks:

- In the 4th harmonic, the maximum bunch length is limited by the AC Robinson instability.
- There is no problem to have long bunches at low current (single bunch mode) because the HC is a super conducting cavity (high shunt impedance).
- The maximum bunch length obtained is very limited in ¾ mode because of a very strong transient beam loading !

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Main Cavity TBL

Why the TBL is so important in SOLEIL Upgrade case:

- The voltage transient $\Delta V = V_{br}\tau_g$ depends only on the gap, the cavity and the beam current.
- The phase transient $\Delta\theta \approx \frac{\Delta V}{V_c}\sin\phi + \cdots$ depends also on the total voltage V_c and the synchronous phase ϕ_s.

Gap duration

$$\Delta V = V_{br}\tau_g = \frac{2IR_s}{1+\beta}\frac{\Delta T_g}{T_f}$$

Cavity filling time

Cavity coupling

$$\tau_g = \frac{\Delta T_g}{T_f}$$

$$\Delta\theta \approx \frac{\Delta V}{V_c}\sin\phi_s + \cdots$$

$$V_{br} = \frac{2IR_s}{1+\beta}$$

Configuration	$\Delta\theta$	T_f	ΔT_g	τ_g	V_{br}	**ΔV**	V_c
SOLEIL ¾ (450 mA), SC	4,4 ps	**45,2 μs**	0,3 μs	0,006	4,1 MV	27 kV	**2,8 MV**
SOLEIL-U ¾ (450 mA), NC	**62,5 ps**	**5,5 μs**	**0,3 μs**	**0,054**	**3,1 MV**	**169 kV**	**1,4 MV**
SLS ¾ (200 mA), NC	7,0 ps	**8,5 μs**	**0,24 μs**	0,028	**1,7 MV**	47 kV	**2,2 MV**

Impact of TBL on bunch lengthening

For SOLEIL-U with ESRF-EBS type cavities, the phase transient provided by main RF cavities is of the same order of magnitude compared to the width of the flat potential (in the ideal case)!

So to reduce TBL, we need to avoid:

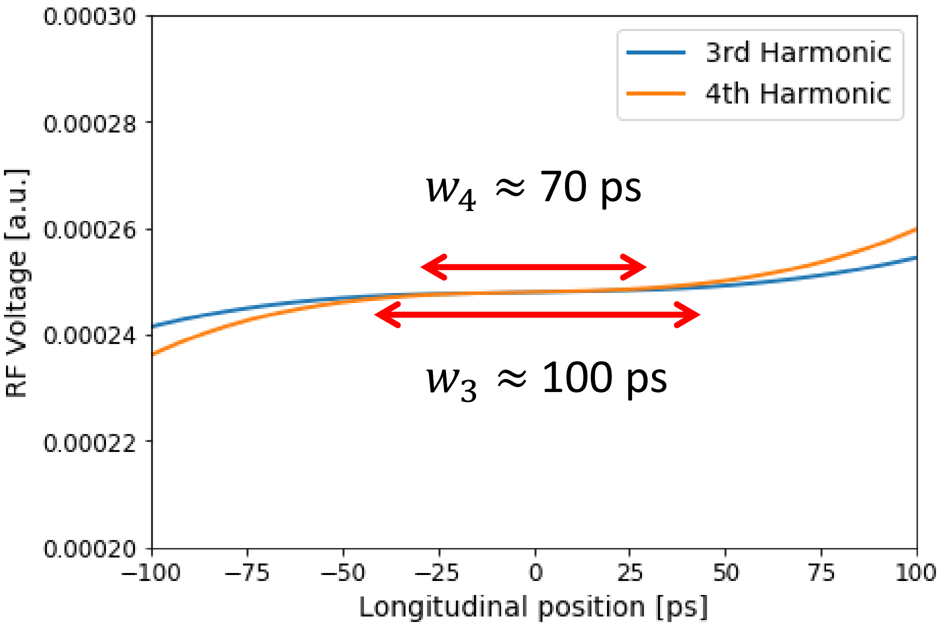
- High R/Q cavities
- Long gap (so longer rings for fixed filling factors)
- Low RF Voltage

SOLEIL-U ¾ (450 mA)

Main RF Voltage	Phase shift induced by Main RF
1,2 MV	77,1 ps
1,4 MV	62,5 ps
1,7 MV	49,2 ps
2 MV	40,7 ps
2,2 MV	36,6 ps

The TBL from main cavity explains some of the difficulties in lengthening the bunches in this configuration.

When both systems, fundamental and harmonic, are taken into account, the phase shift from the TBL can reach more than 400 ps and remove most of the benefit of the HC in that operation mode.



General message from this talk

- ❑ There are important beam dynamics consequences in the choices between active or passive HC and super or normal conducting HC.
  - ➢ Passive normal conducting HC induces asymmetric bunch profiles if not at design current
  - ➢ Passive super conducting HC always induces asymmetric bunch profiles

- ❑ Be very careful when you design your HC system.
  - ➢ The double bump bunch profile generally happens if you tune your HC past the minimum of $\frac{dV_{tot}}{dt} \approx 0$
  - ➢ The AC Robinson instability can limit the maximum bunch length you can achieve

- ❑ Asymmetric filling pattern can lead to severe transient beam loading, to avoid that try to:
  - ➢ Use cavity with lower R/Q.
  - ➢ Use higher main cavity RF voltage.
  - ➢ Shorter gaps …
  - ➢ "Guard" bunches (=use different current per bunch, typically higher current in the head and tail of the bunch train).
  - ➢ Feedforward system with dedicated cavity (see N. Yamamoto paper about transient beam loading compensation).

Thank you for your attention!

Backup

Simulation parameters for SOLEIL-U

Lattice : SOLEIL_U_74BA_HOA_SYM04_V0200

$$\alpha_c = 9{,}4 \times 10^{-5}$$
$$U_0 \approx 682\ keV$$
$$\tau_s = 11{,}9\ ms$$
$$\sigma_{s0} = 9{,}2\ ps$$

Value with IDs

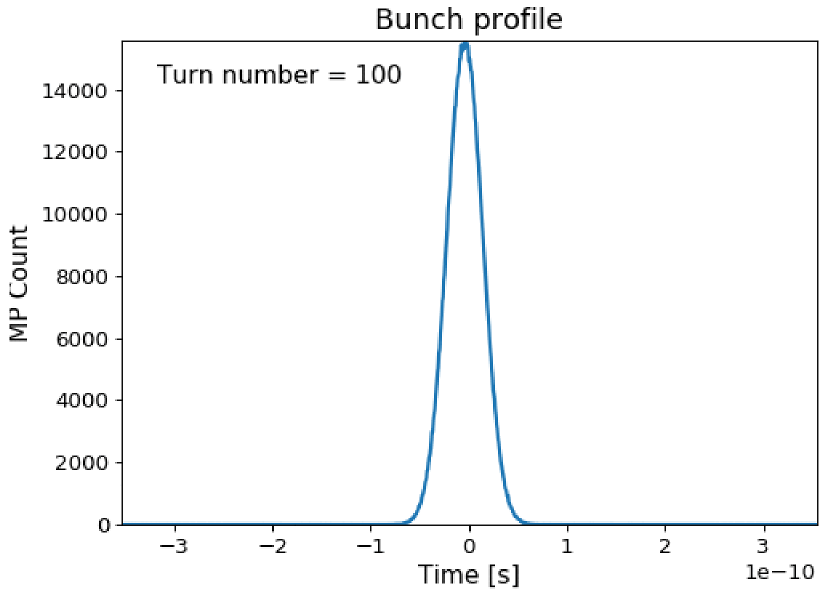
Main cavity:
- $R_s = 19{,}6\ M\Omega$
- $Q_0 = 34\ 000$
- $Q_L = 6\ 000$
- $V_{RF} = 1{,}4\ MV$

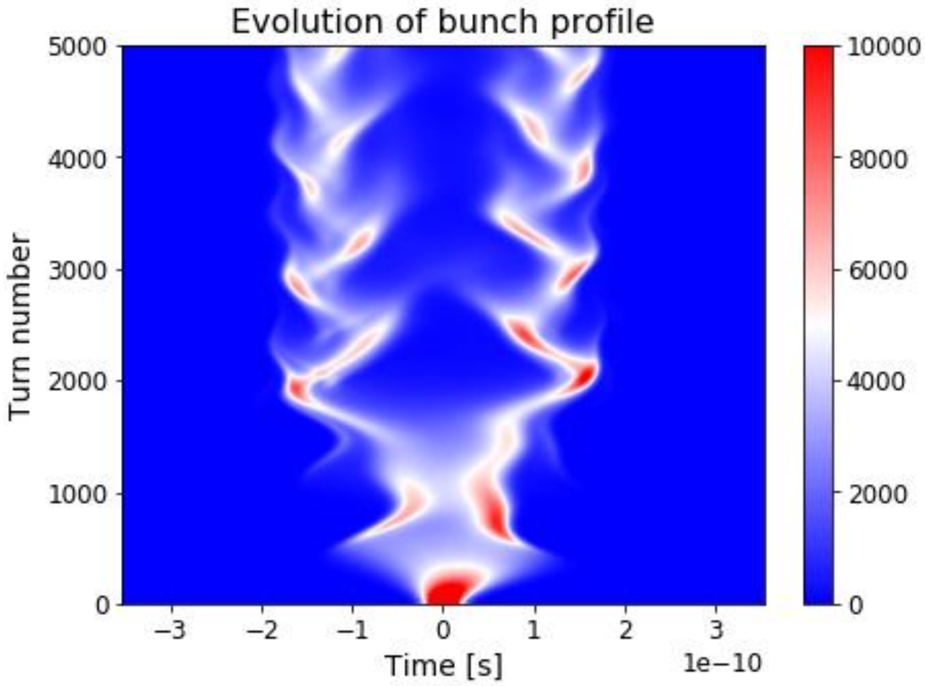
Passive harmonic cavity:
- $m = 4$ (or 3)
- $R_s = 90 \times 10^8$
- $Q_0 = 1 \times 10^8$
- $Q_L = 1 \times 10^8$

Higher order Robinson instability

Recently, a coupled bunch instability was predicted for ALS case by M. Venturini (ALS) using perturbation theory (Vlasov equation). The instability seems to be driven by the imaginary part of the cavity impedance rather than by its real part.

Using the parameters given in the paper, it was possible to reproduce the instability:





Venturini, M. (2018). Passive higher-harmonic rf cavities with general settings and multibunch instabilities in electron storage rings. *Physical Review Accelerators and Beams*, *21*(11), 114404.

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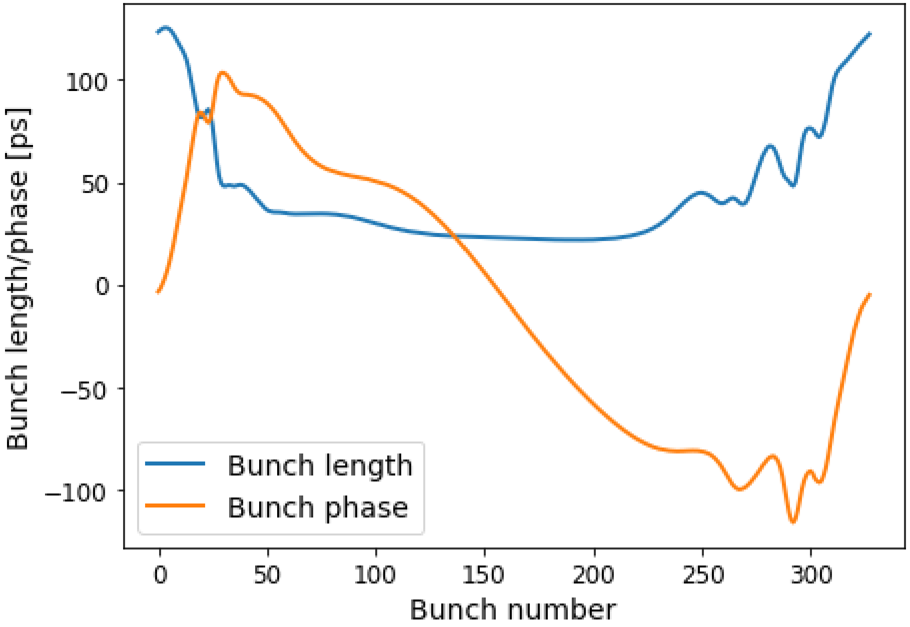


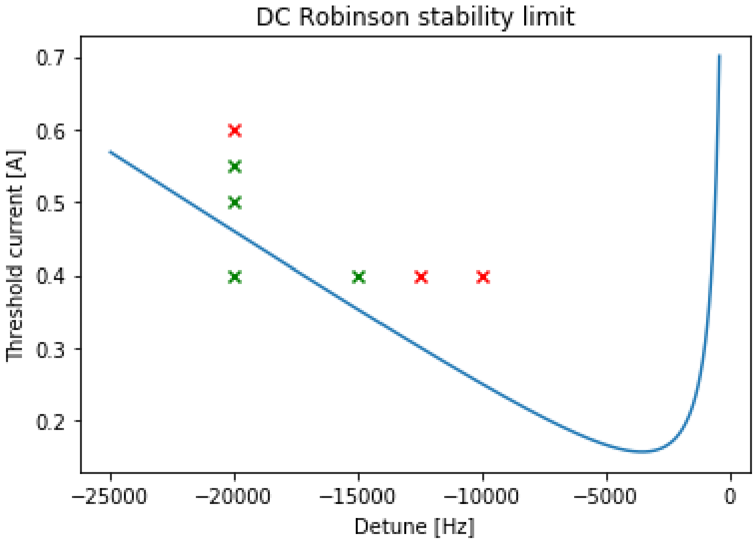
Venturini, M. (2018). Passive higher-harmonic rf cavities with general settings and multibunch instabilities in electron storage rings. *Physical Review Accelerators and Beams*, *21*(11), 114404.

Benchmark

This algorithm has been implemented in the multi-bunch tracking code *mbtrack* (by N. Yamamoto). Using *mbtrack*, it was possible to reproduce different instabilities and the transient beam loading effect:

- DC (static) Robinson
- Transient beam loading
- AC Robinson (coupled bunch)
- Cavity HOM

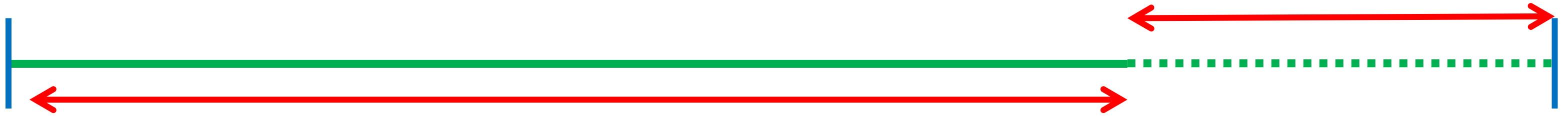
$$2V_c \sin(\phi) + V_{br} \sin(2\psi) > 0$$



Wilson, P. B. (1994). Fundamental-mode rf design in e+ e− storage ring factories. In Frontiers of Particle Beams: Factories with e+ e-Rings (pp. 293-311). Springer, Berlin, Heidelberg.

TBL theory (for a single cavity)

Beam filling:



ΔT_g= gap duration

$T_b = T_0 - \Delta T_g =$ beam duration

If the two conditions are verified:

- The gap duration ΔT_g is long compared to the cavity filling time $T_f \Leftrightarrow \tau_g = \frac{\Delta T_g}{T_f} \ll 1$
- The beam duration T_b is long compared to the cavity filling time $T_f \Leftrightarrow \tau_b = \frac{T_b}{T_f} \gg 1$

Then the voltage and phase transient for **main RF**, ΔV and $\Delta\theta$, can be expressed very simply as:

$$\Delta V = V_{br}\tau_g$$

$$T_f = \frac{2Q_L}{\omega_r}$$

$$\Delta\theta \approx \frac{\Delta V}{V_c}\sin\phi + \left[\sqrt{\tan^2\phi + 2\frac{\Delta V}{V_c}\cos\phi} - \tan\phi\right]$$

$$V_{br} = \frac{2IR_s}{1+\beta}$$

Wilson, P. B. (1994). Fundamental-mode rf design in e+ e− storage ring factories. In Frontiers of Particle Beams: Factories with e+ e-Rings (pp. 293-311). Springer, Berlin, Heidelberg.

Main Cavity TBL

For the usual parameters (SOLEIL, SLS, SOLEIL-U) and gaps, the second condition $\tau_b \gg 1$, is never valid …

But the formula still seems to work quite well to predict simulation data:

Configuration	Main RF type	Formula	mbtrack
SOLEIL ¾ (450 mA)	SC	4,4 ps	4,7 ps
SOLEIL-U ¾ (450 mA)	**NC**	**62,5 ps**	**61,8 ps**
SLS ¾ (200 mA)	NC	7,0 ps	6,9 ps

Why such a difference between SOLEIL-U and SLS, which are both using normal conducting cavities (NC) for main RF ?

- Factor 2,25 between SLS and SOLEIL-U in current
- Factor 9 between SLS and SOLEIL-U in phase shift