Simulation results for the SOLEIL Upgrade

Alexis Gamelin on behalf of the SOLEIL upgrade team

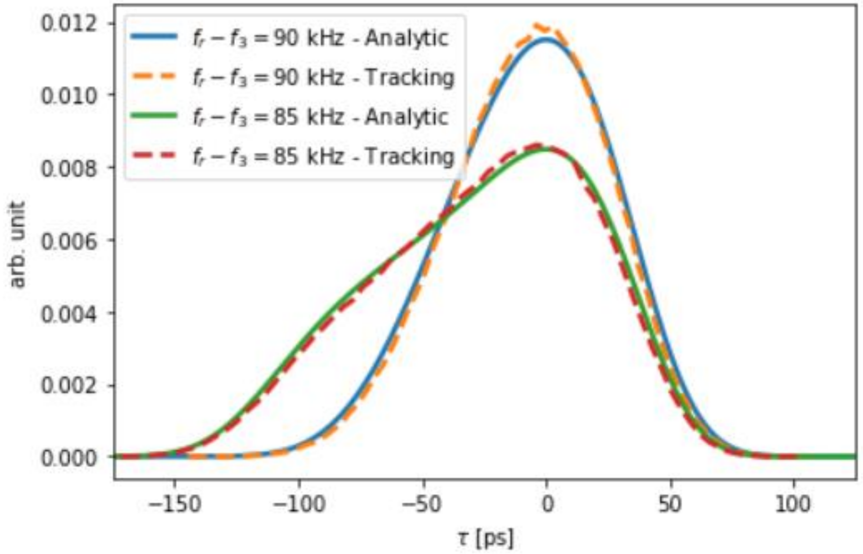
1. Beam dynamics with a 3rd harmonic cavity
2. Lifetime increase with a 3rd harmonic cavity
3. Impact of non-uniformities of the beam filling pattern
4. Decrease of the HOM instability threshold due to the harmonic cavity

Mini workshop of WP2 RF collaboration
23/06/2021

All the tracking results in this talk are obtained using mbtrack2 [1]:

- Multi-bunch python tracking code using $10^4 - 10^5$ macro-particules per bunch in parallel.
- Using the CavityResonator class allows to simulate active/passive RF cavities with beam loading.
- The implementation of this class is very similar to what can be found in the SOLEIL/KEK mbtrack version [2].
- Open source: https://gitlab.synchrotron-soleil.fr/PA/collective-effects/mbtrack2

The analytic calculations of the bunch profile are obtained by solving an equation system similar to a Haïssinski equation [3]. The method is available in mbtrack2 code library.



[1] A. Gamelin, W. Foosang, and R. Nagaoka, “mbtrack2, a Collective Effect Library in Python”, IPAC'21 MOPAB070.

[2] N. Yamamoto, A. Gamelin, and R. Nagaoka, "Investigationof Longitudinal Beam Dynamics With Harmonic Cavities by Using the Code mbtrack" *IPAC’19* MOPGW039

[3] A. Gamelin and N. Yamamoto, “Equilibrium Bunch Density Distribution With Multiple Active and Passive RF Cavities”, IPAC'21 MOPAB069.

Simulation Parameters

The parameters used for the simulations shown here are:

RF parameters:

Main cavity (4 ESRF-EBS type):

- $m = 1$
- $R_s = 19{,}6\ M\Omega$
- $Q_0 = 34\ 000$
- $Q_L = 6\ 000$
- $V_{RF} = 1{,}7\ MV$

Passive harmonic cavity (2 Super3HC type):

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

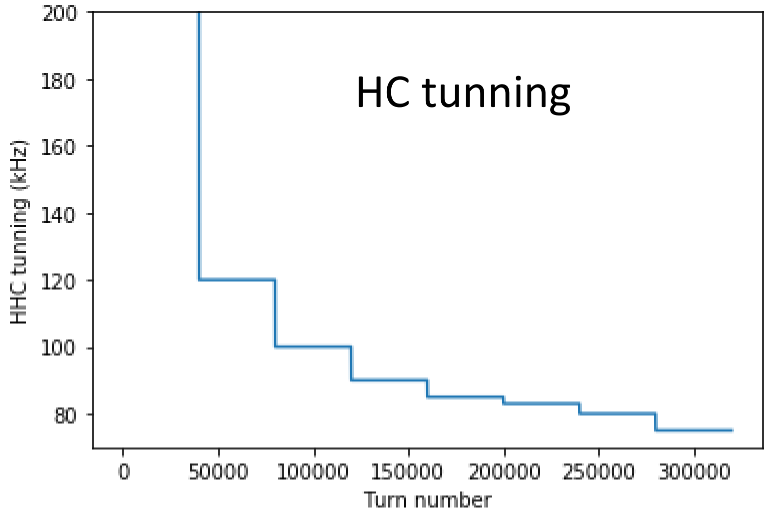
SOLEIL Upgrade CDR (v0313):

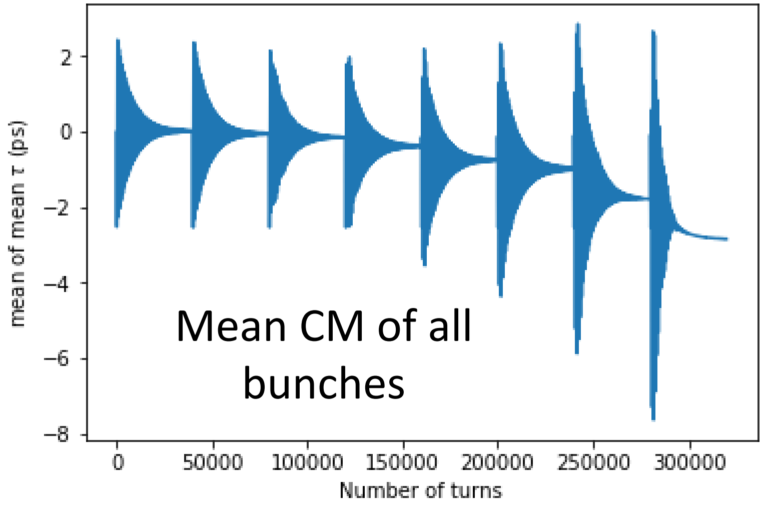
- $h = 416$
- $L = 354{,}73\ m$
- $E_0 = 2{,}75\ GeV$
- $\epsilon_x/\epsilon_y = 52\ pm.rad$
- $\nu_x/\nu_y = 0{,}2/0{,}2$
- $\tau_x/\tau_y = 9{,}2/9{,}3\ ms$
- $\tau_s = 11{,}3\ ms$
- $\alpha_c = 9{,}12 \times 10^{-5}$
- $\sigma_0 = 8\ ps$
- $\sigma_\delta = 9 \times 10^{-4}$
- $U_0 = 515\ keV$ (w/o IDs)

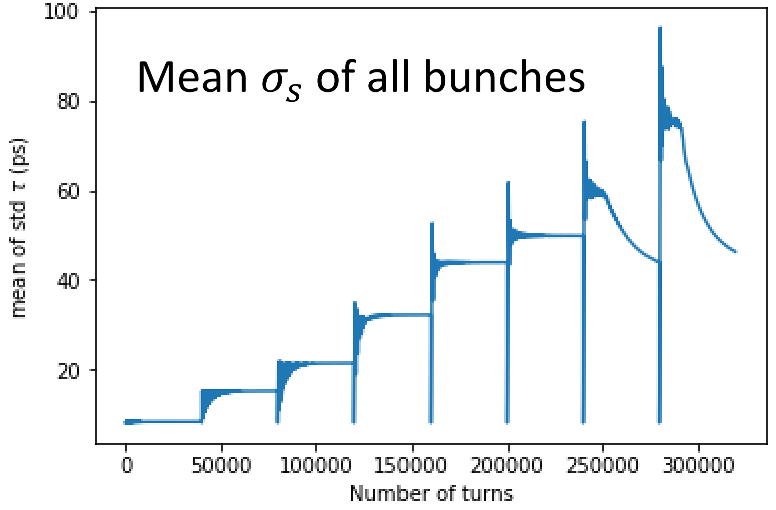
- No feedback of any sort for the both main and harmonic cavities.
- Main cavity is set to a given tunning (usual close to the optimal tunning point) and the generator voltage is computed to get the design voltage and phase.
- For the passive harmonic cavity, the tunning is the only knob to adjust the voltage.

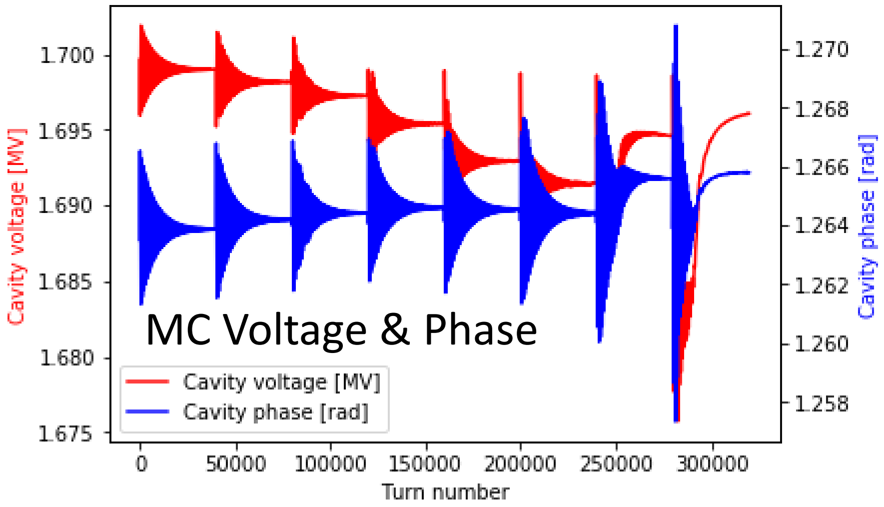
Beam dynamics with a 3rd harmonic cavity

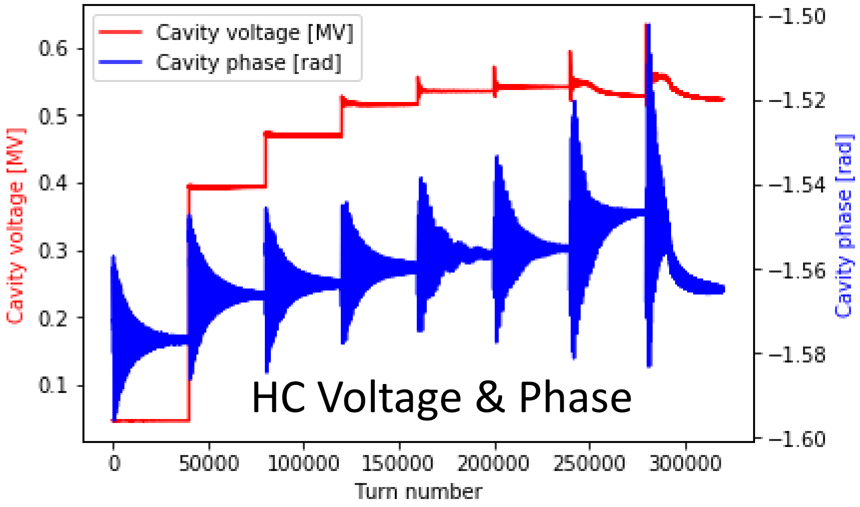
Scanning of the HC tunning with MC voltage and phase fixed:





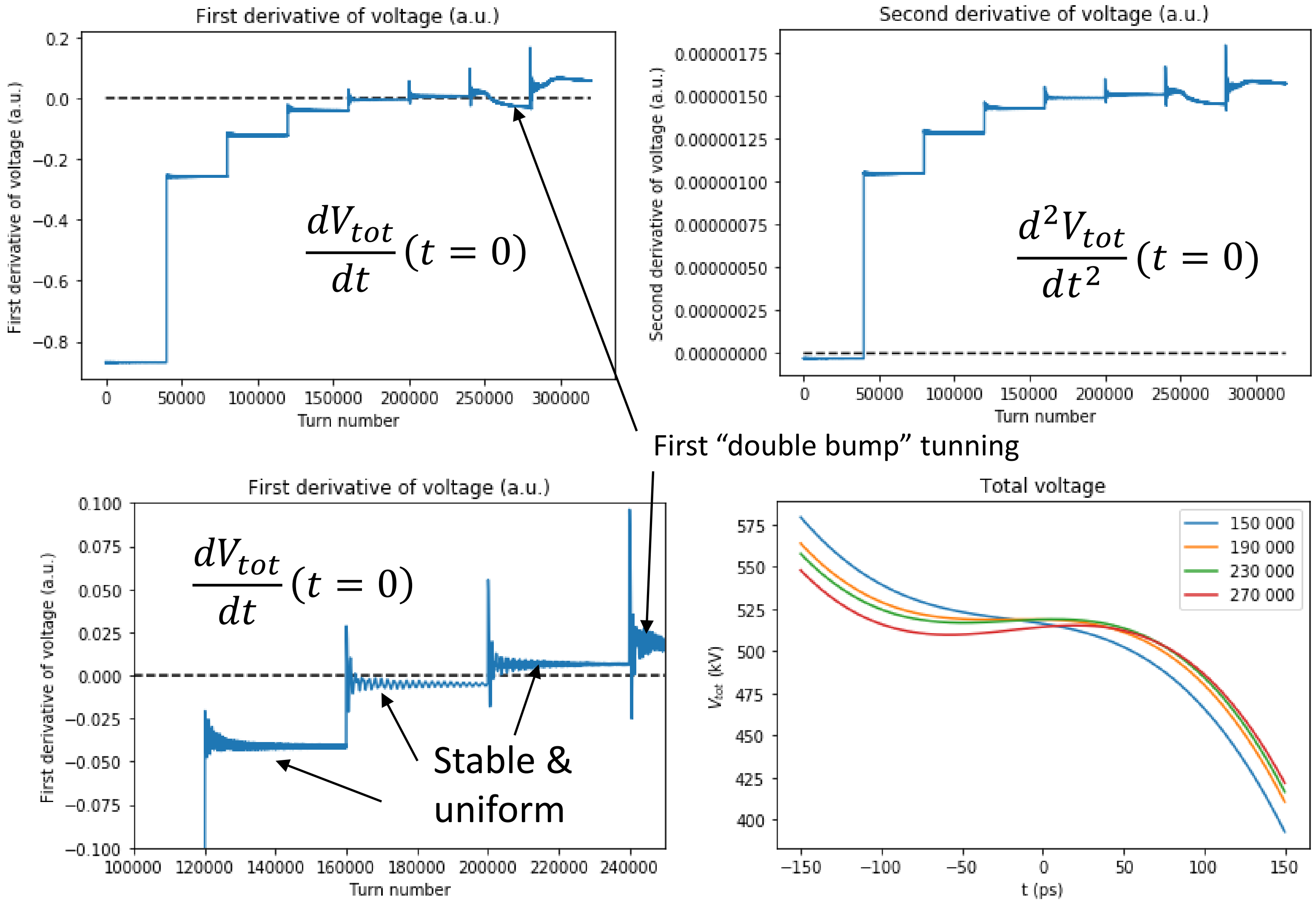






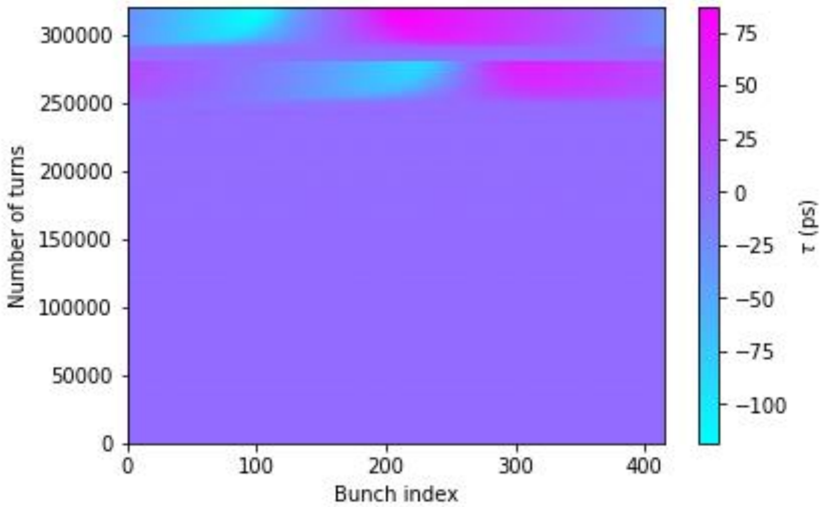
Beam dynamics with a 3rd harmonic cavity

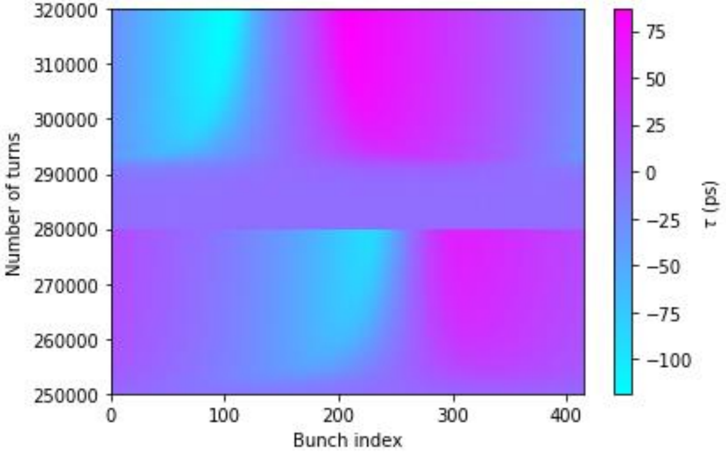
- As expected with a SC passive HC, it is only possible to cancel $\frac{dV_{tot}}{dt}$ and not $\frac{d^2V_{tot}}{dt^2}$.
- As it is not possible to reach plat potential conditions ($\frac{dV_{tot}}{dt} = \frac{d^2V_{tot}}{dt^2} = 0$), the bunch profile is asymmetric.
- Here the first tunning past the flat potential (i.e. with a positive slope) still gives a stable beam without double bump profile.
- Then, when the positive slope is more important, the double bump regime starts to appear.
- Push past the double bump regime, a fast loss of all bunches is observed (oscillations of bunch profile with a mix of modes m=0,1,2… and dipole coupled bunch motion l=0)

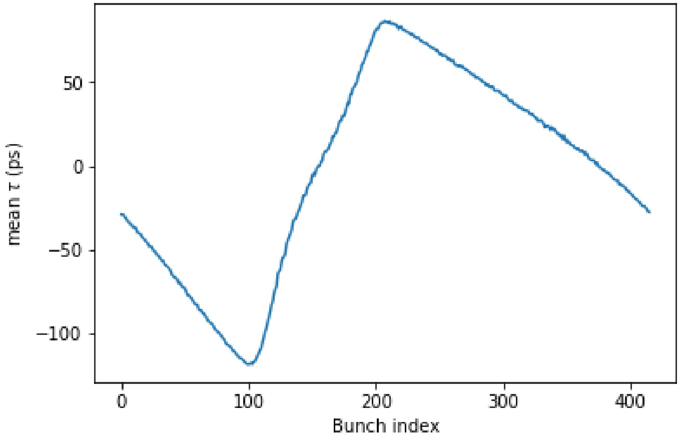


Beam dynamics with a 3rd harmonic cavity

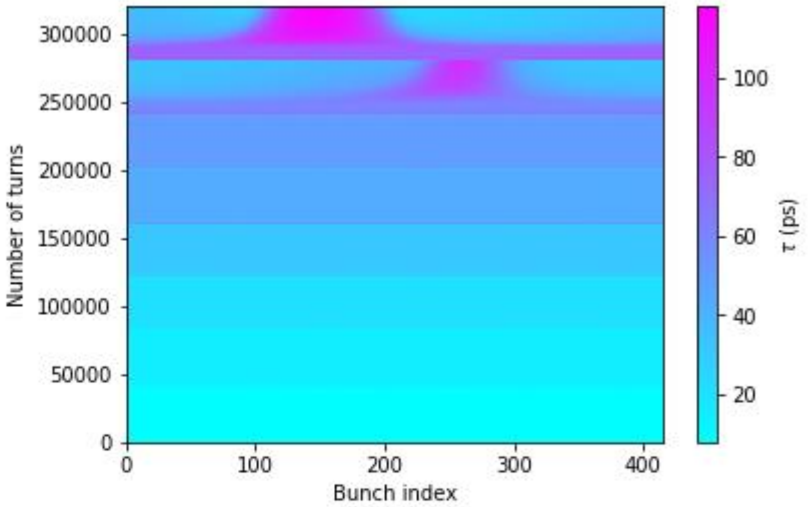
CM vs index



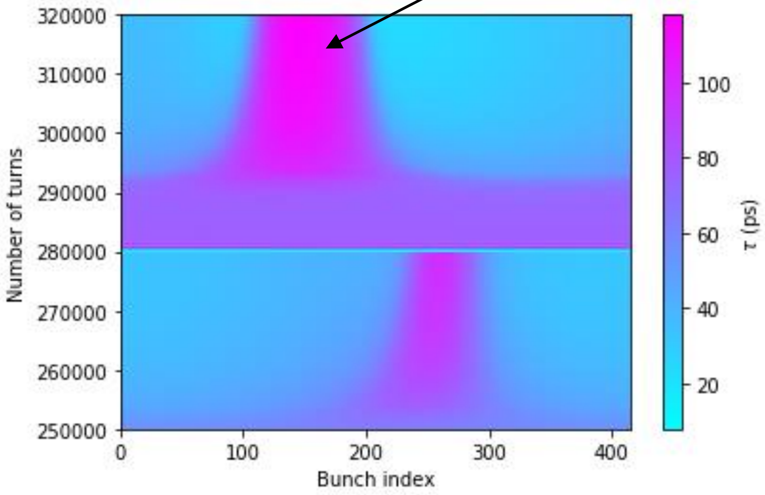


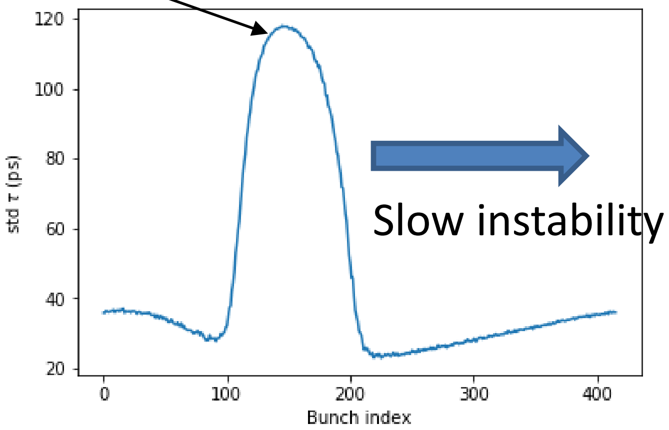


σ_s vs index



“Double bump”





Slow instability ?

Lifetime increase with a 3rd harmonic cavity

In the Piwinski lifetime formula, the lifetime τ is proportional to $\int \rho^2(z)dz$. So the lifetime increase one can expect from the bunch lengthening is proportional to [1] :

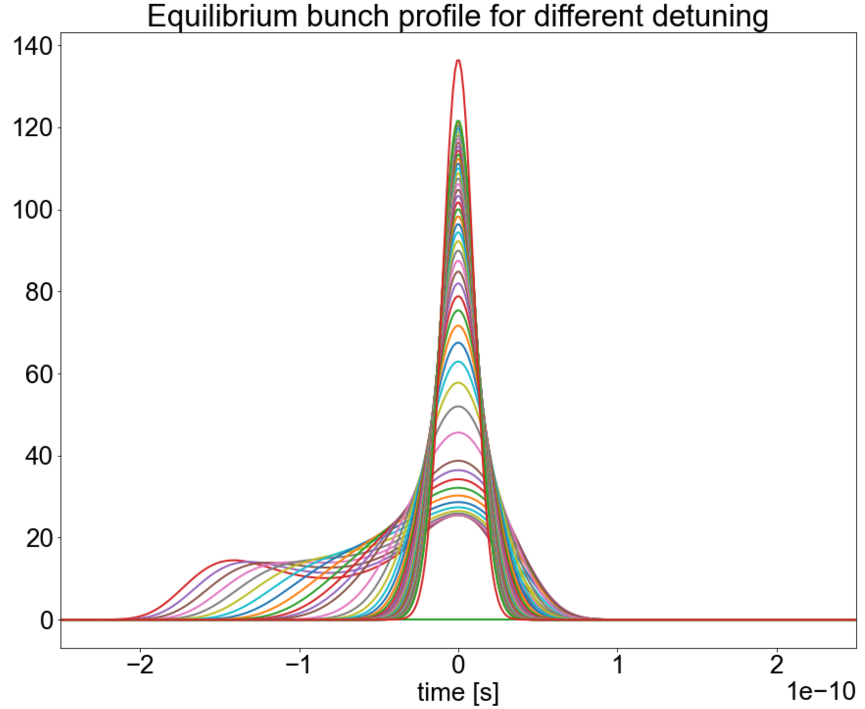
$$R \approx \frac{\int \rho_0^2\,(z)dz}{\int \rho^2\,(z)dz}$$

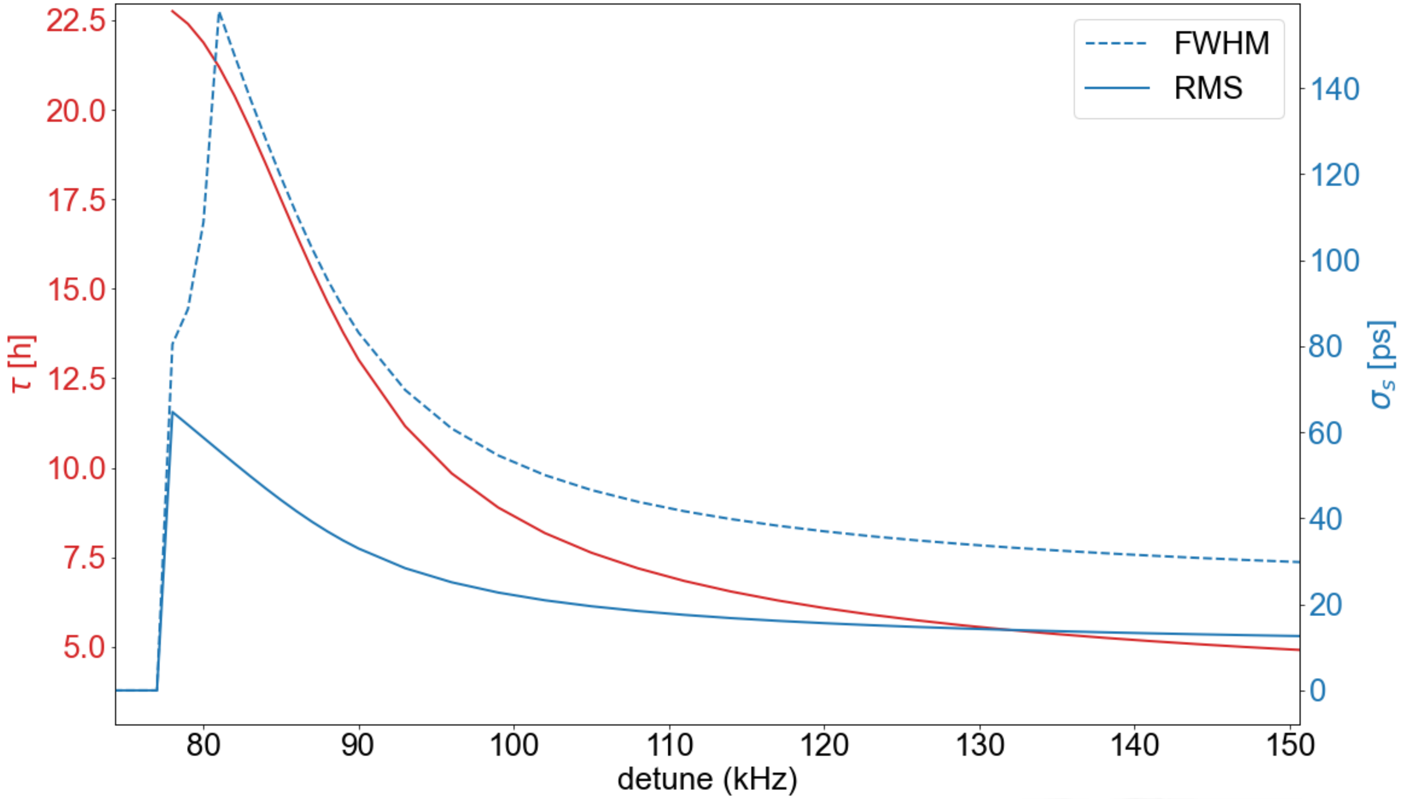
w/o HC

w/ HC

Assuming:

- $\tau_0 = 3{,}5\ h$ for 1,2 mA/bunch without HC
- $\sigma_0 = 9\ ps$
- Round beam $\epsilon_{x,y} = 50\ pm.rad$
- No IDs & no errors





[1]Warnock, R., & Venturini, M. Equilibrium of an arbitrary bunch train in presence of a passive harmonic cavity: Solution through coupled Haïssinski equations.

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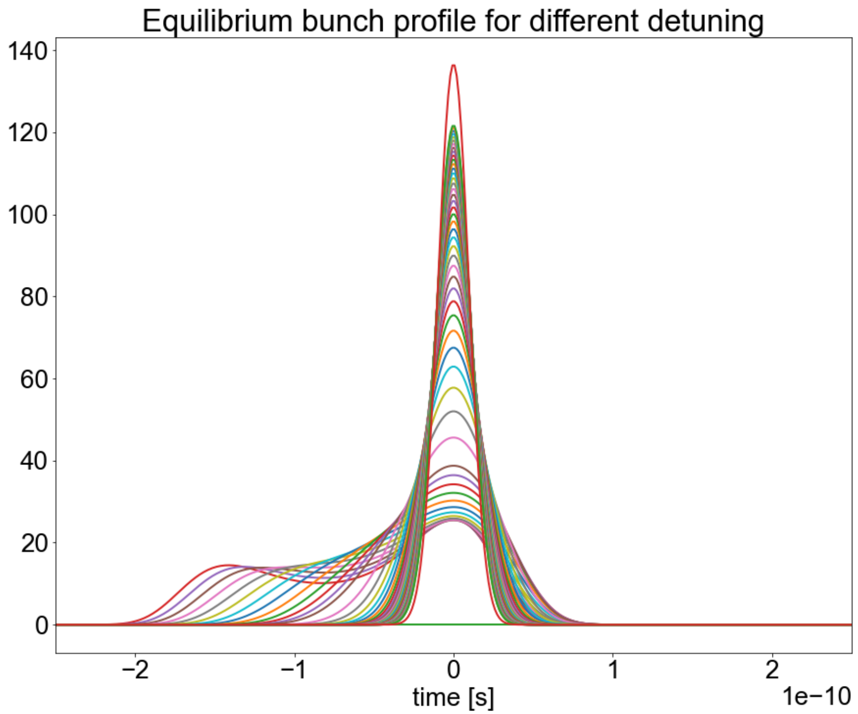

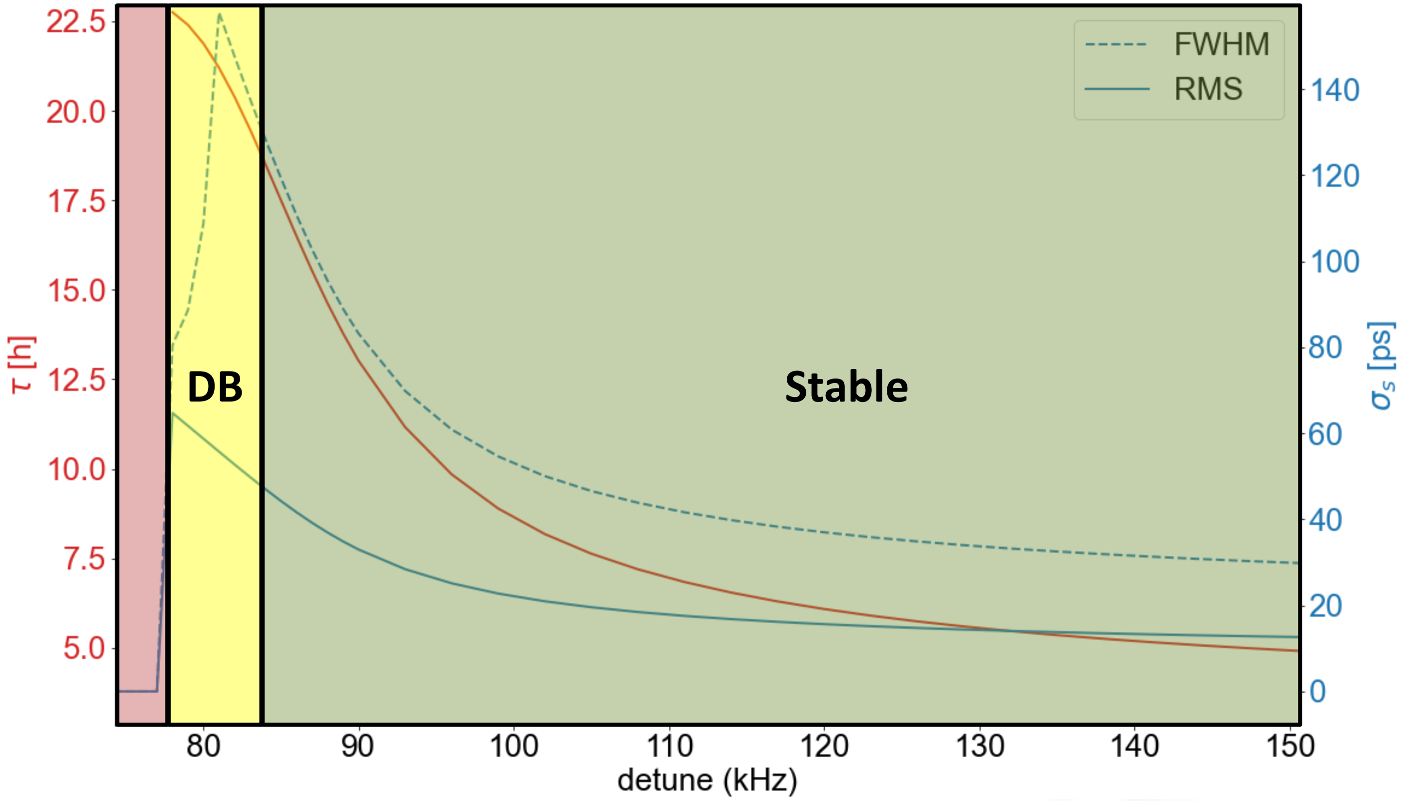

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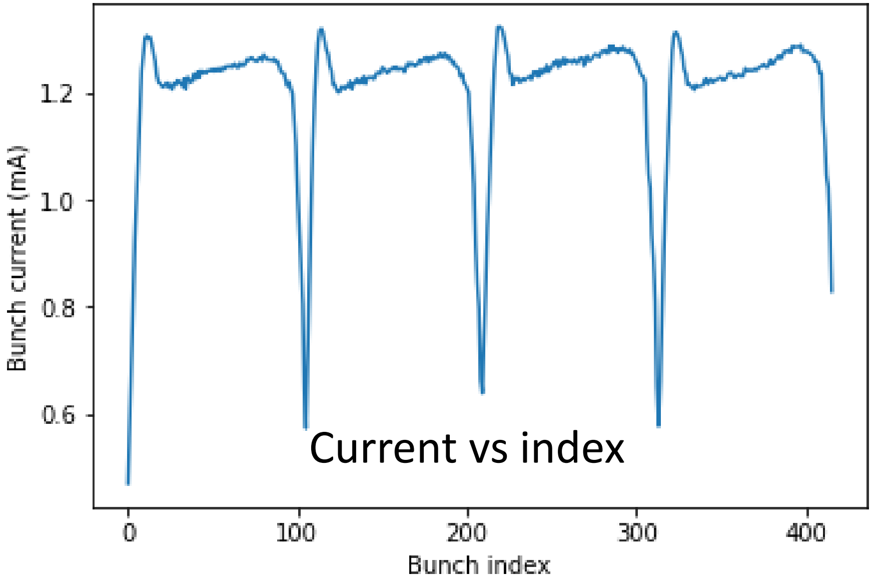
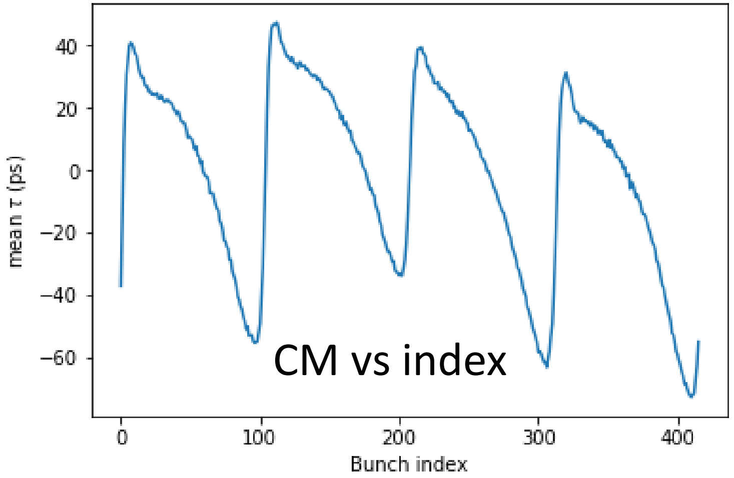
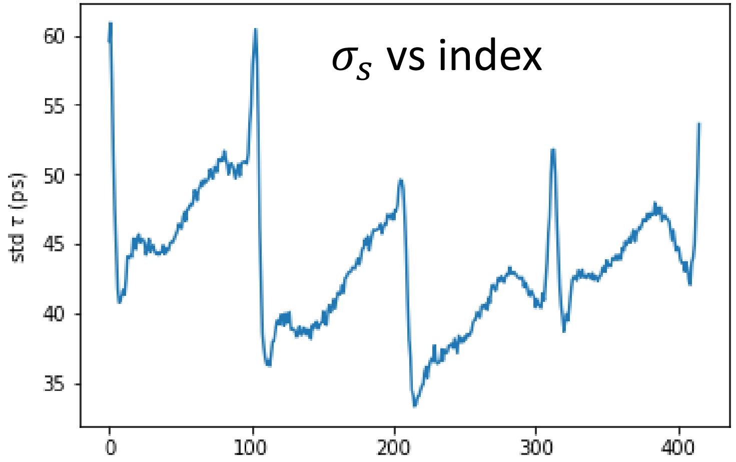
Impact of non-uniformities of the beam filling pattern

In today SOLEIL, the “uniform” filling pattern is injected by steps of 104 bunches (¼ of the full filling). Due to the transmission from the booster, there is some variation of the current per bunch depending on the bunch index as shown in the **measured filling pattern taken during an operation run**:

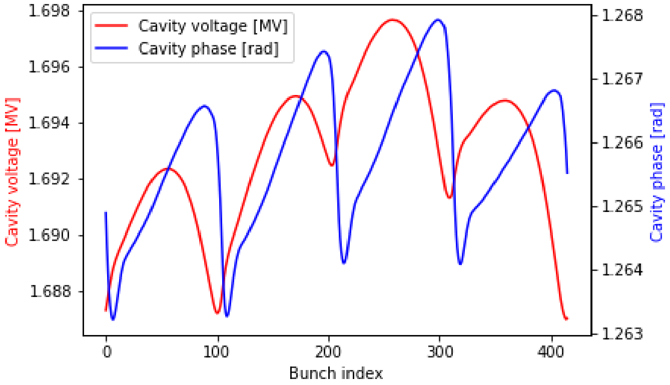


Using this filling pattern as input in the simulation, for an HC set near the flat potential, we get strong variation of the phase and bunch length versus bunch index:

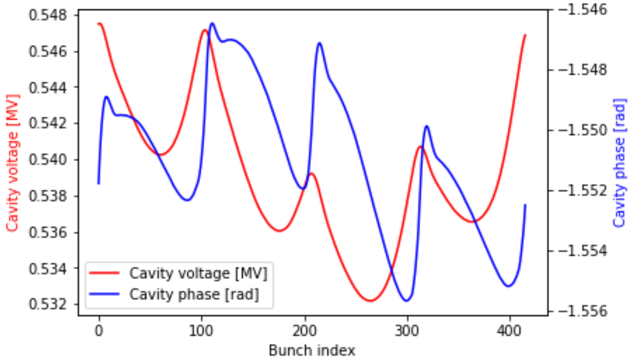




MC voltage & phase vs index



HC voltage & phase vs index

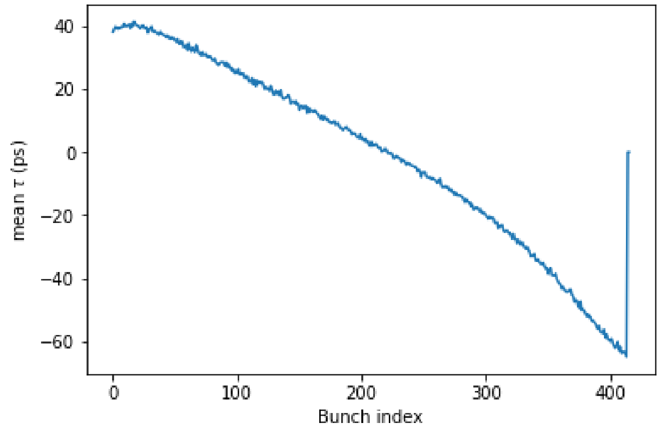


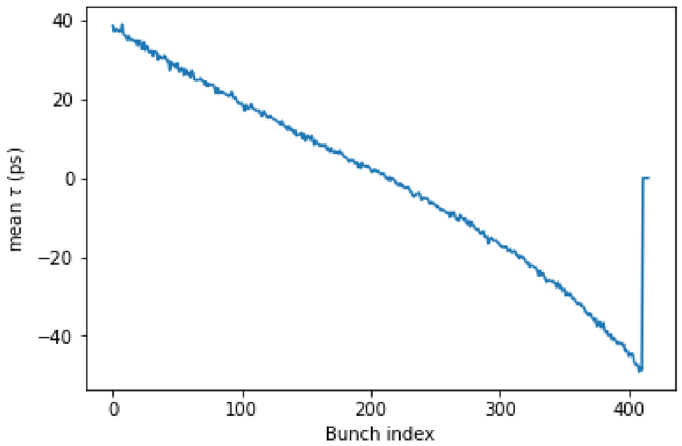
Impact of gaps in the beam filling pattern

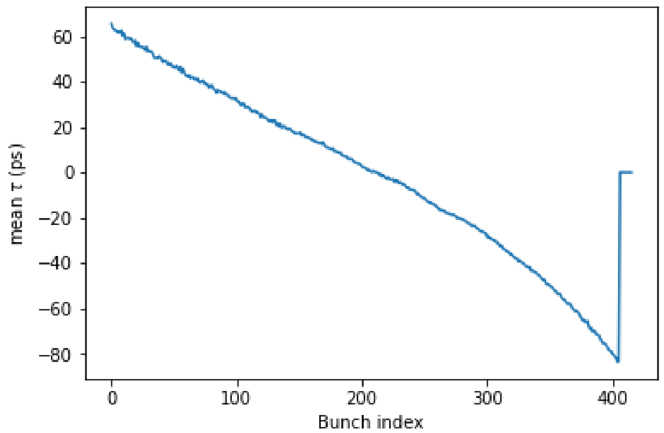
We will also need the possibility to have a small gap during user mode if needed to clear the ions.

	Gap of 2 bunches	**Gap of 5 bunches**	**Gap of 10 bunches**
Phase shift from MC alone	6 ps	16 ps	32 ps

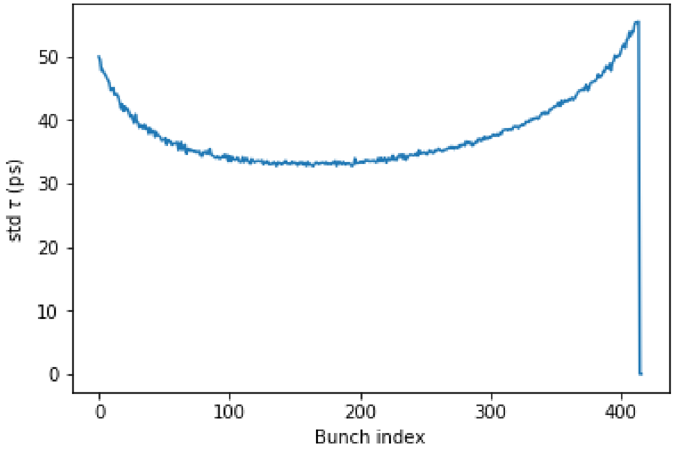
CM vs index

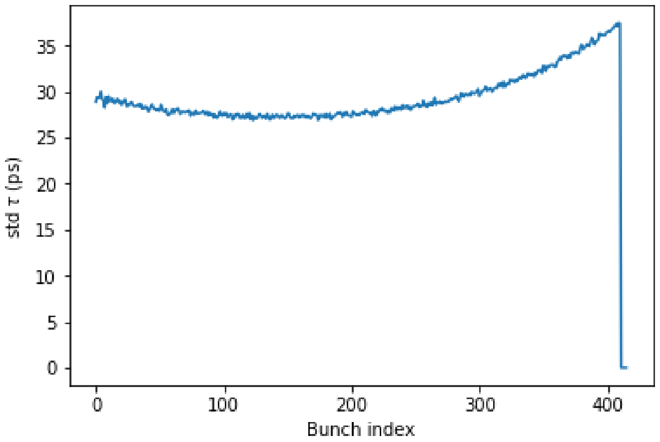


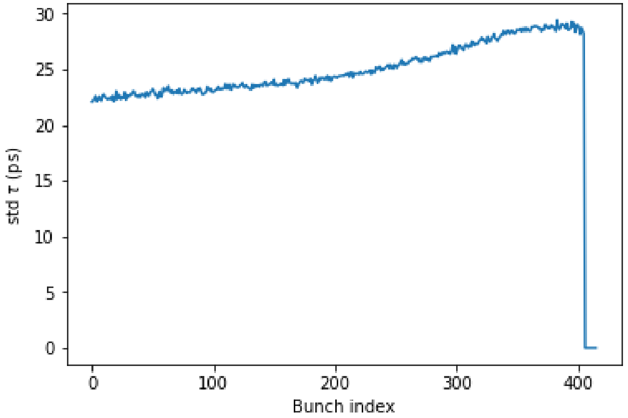




σ_s vs index







HOM Instability

Now let us have a look at the longitudinal coupled-bunch instability (LCBI) driven by the HOM of the main cavity and how the harmonic cavity may impact this instability.

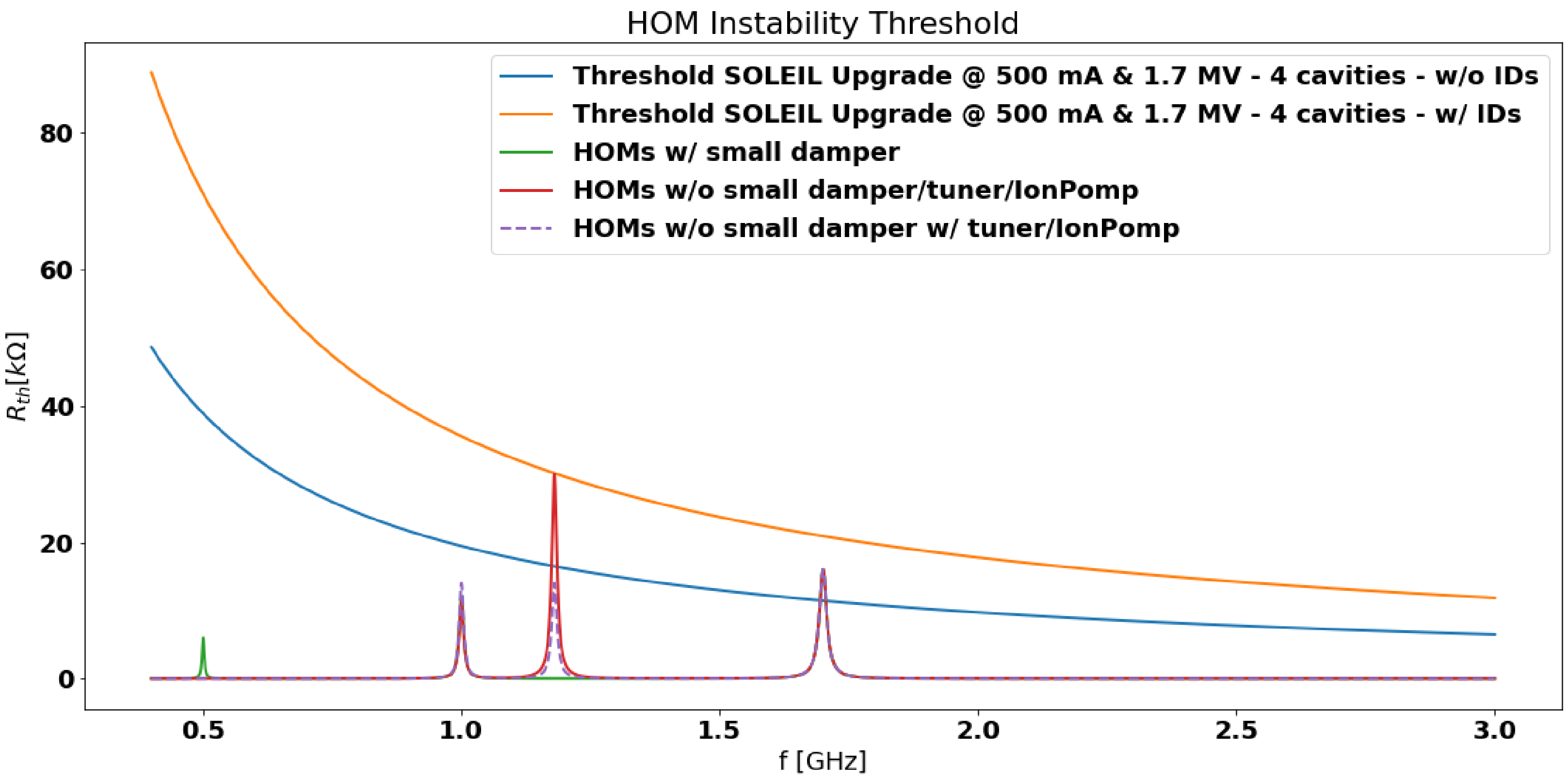
The HOM instability is well explained by the LCBI theory:

$$\tau_g^{-1} = \frac{e\alpha I_0}{4\pi E \nu_s}\left\{\sum_{n=0}^{\infty}\omega_{\mu,n}^{+}\,\mathrm{Re}\left[Z(\omega_{\mu,n}^{+})\right] - \sum_{n=1}^{\infty}\omega_{\mu,n}^{-}\,\mathrm{Re}\left[Z(\omega_{\mu,n}^{-})\right]\right\}$$

$$\omega_{\mu,n}^{\pm} = \{nM \pm (\mu + \nu_s)\}\,\omega_0$$

Where the HOM impedance is described by the resonator model:

$$Z(\omega) = \frac{R}{1 + iQ_L\left(\frac{\omega_r}{\omega} - \frac{\omega}{\omega_r}\right)}$$



When the coupled bunch mode frequency coincide with the HOM frequency ($\omega_{\mu,n} = \omega_r$), corresponding to the strongest instability growth rate, the formula simplify to:

$$\boxed{R_{th} = \frac{4\pi}{\tau_s \alpha_c}\frac{E}{I_0}\frac{\omega_s}{\omega_0}\frac{1}{\omega}}$$

HOM Instability

Now let us have a look at the longitudinal coupled-bunch instability (LCBI) driven by the HOM of the main cavity and how the harmonic cavity may impact this instability.

The HOM instability is well explained by the LCBI theory:

$$\tau_g^{-1} = \frac{e\alpha I_0}{4\pi E \nu_s}\left\{\sum_{n=0}^{\infty}\omega_{\mu,n}^{+}\,\mathrm{Re}\left[Z(\omega_{\mu,n}^{+})\right] - \sum_{n=1}^{\infty}\omega_{\mu,n}^{-}\,\mathrm{Re}\left[Z(\omega_{\mu,n}^{-})\right]\right\}$$

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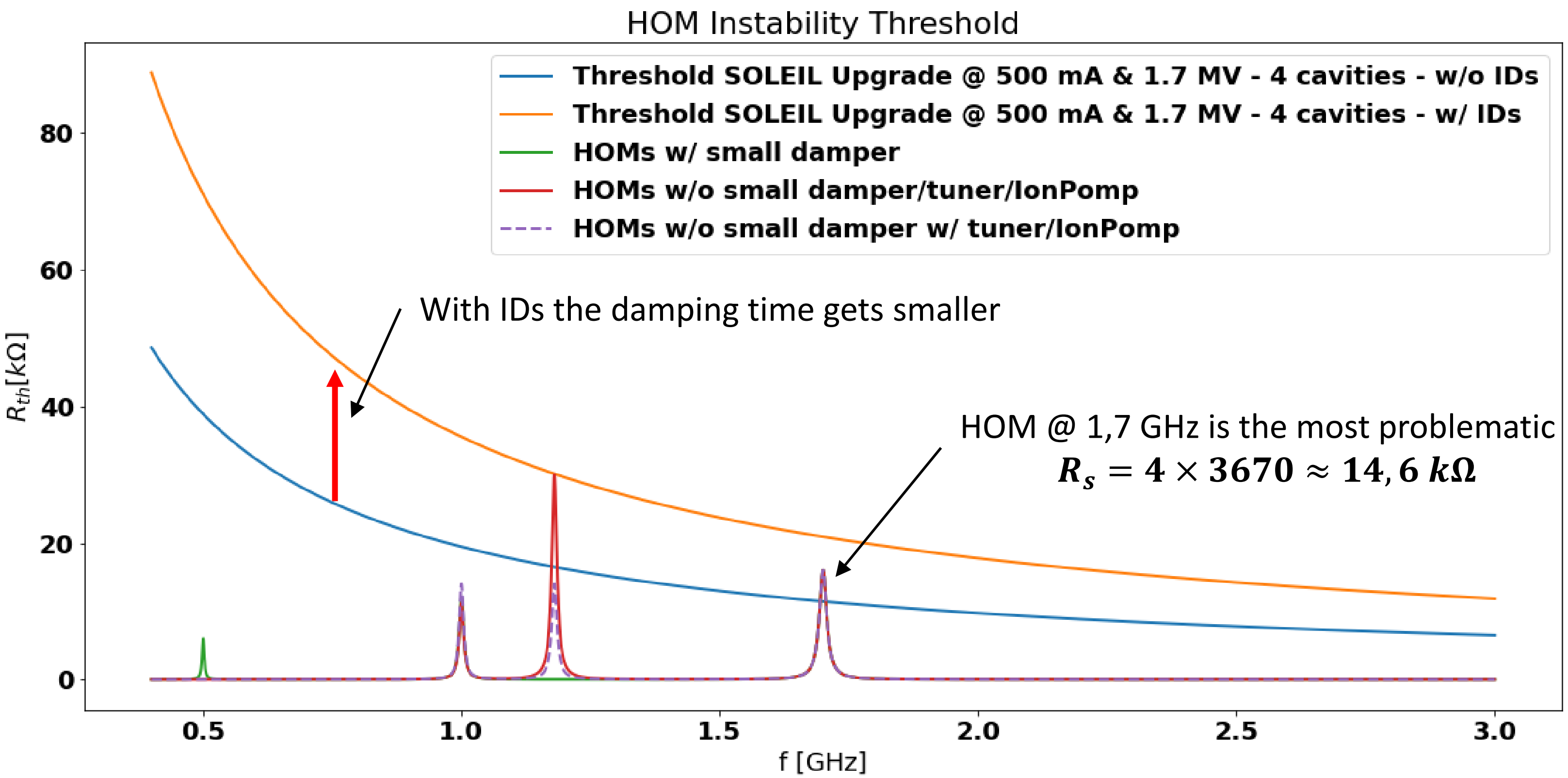

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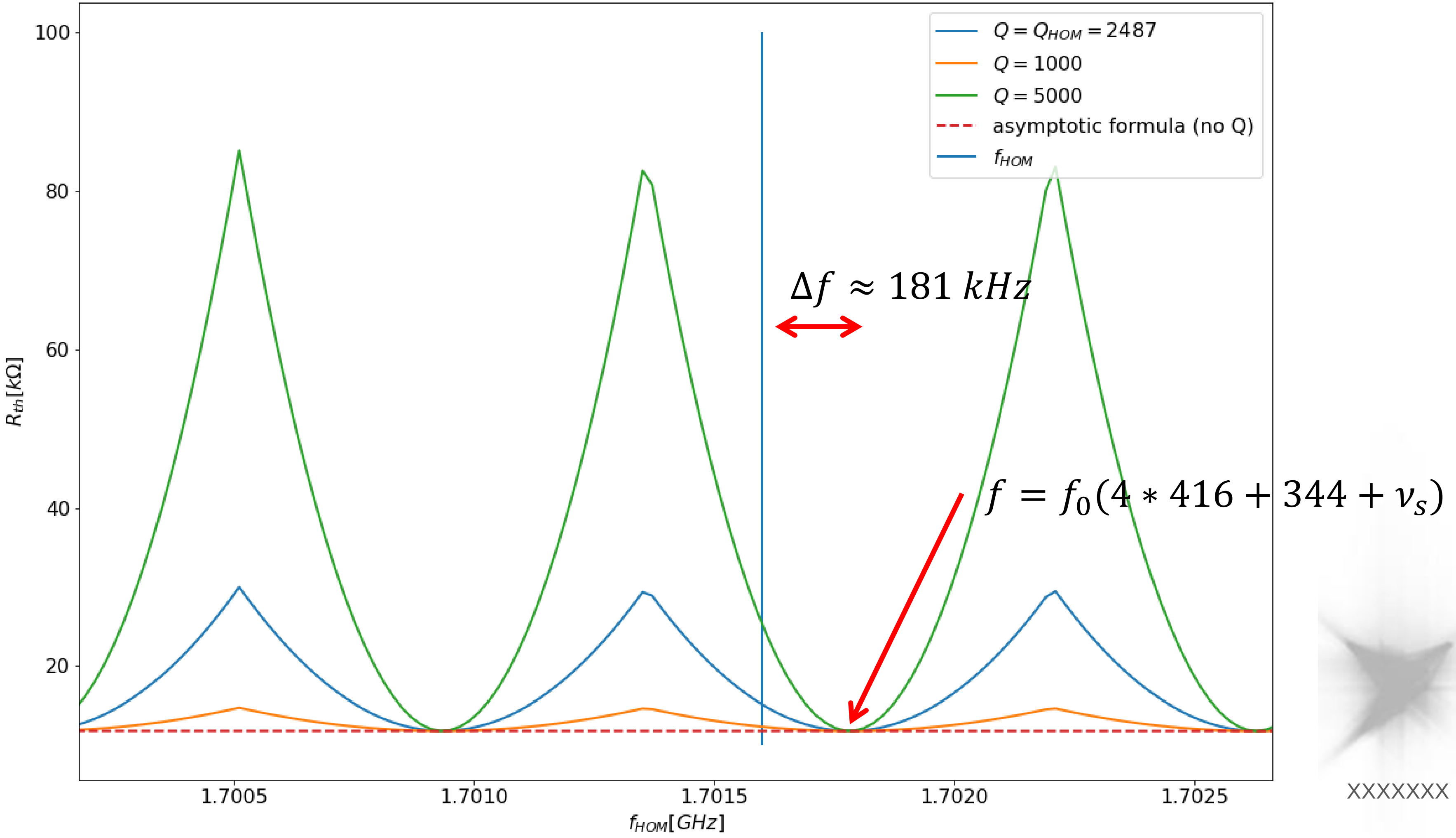
HOM Instability – Q dependance

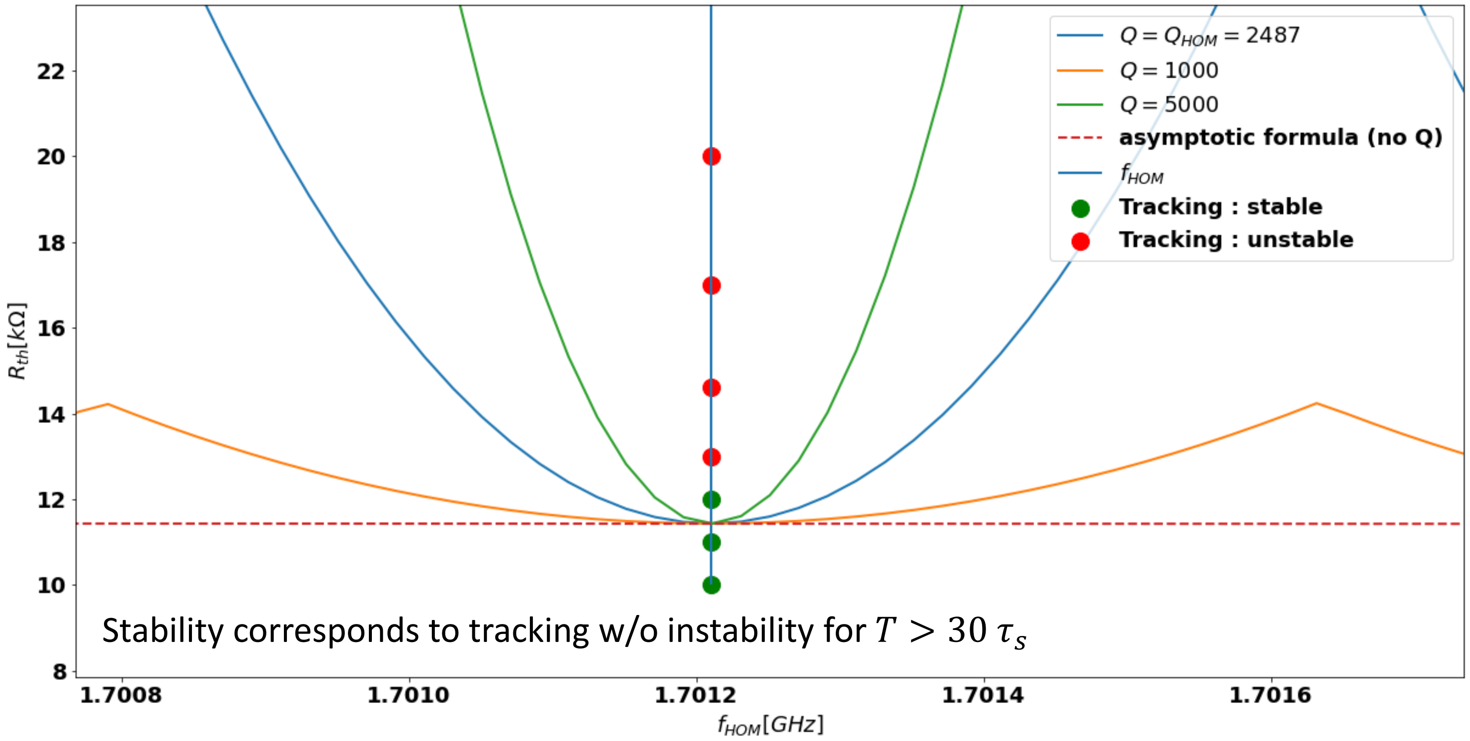
Outside of the resonance, the threshold is strongly dependent on the Q of the HOM.
So as $Q_{HOM} = 2487$, it may give us some margin compared to the asymptotic constant case.
But to prepare for the worst, we still consider that resonance case.

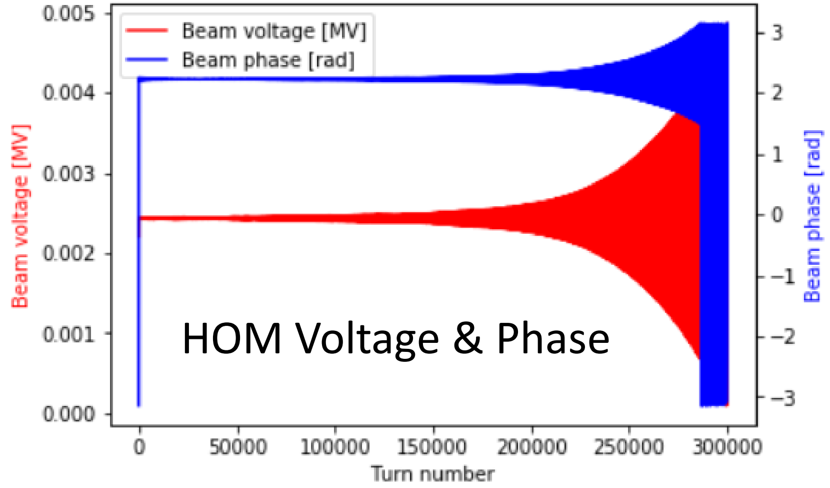


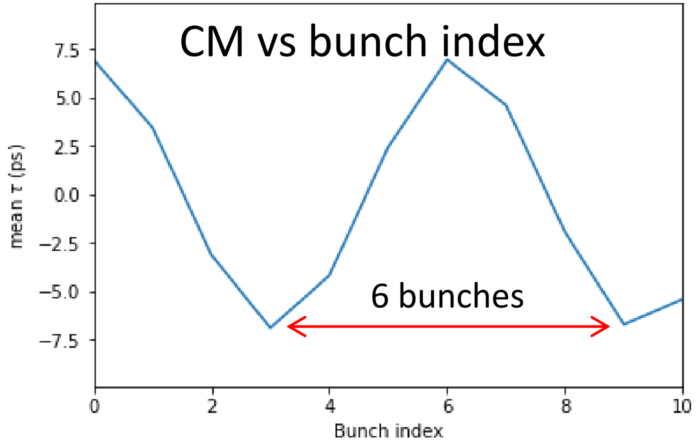
HOM Instability – Tracking

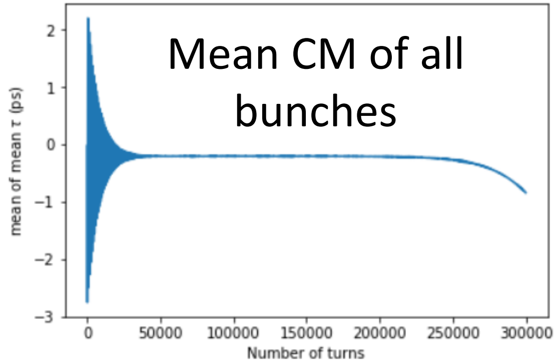
Tracking results agree well with both formulas (LCBI and asymptotic):

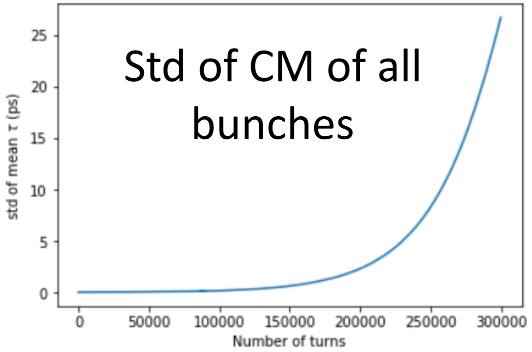
Case : $\boldsymbol{R_s = 14,6\ k\Omega\ -\ Q = 100}$











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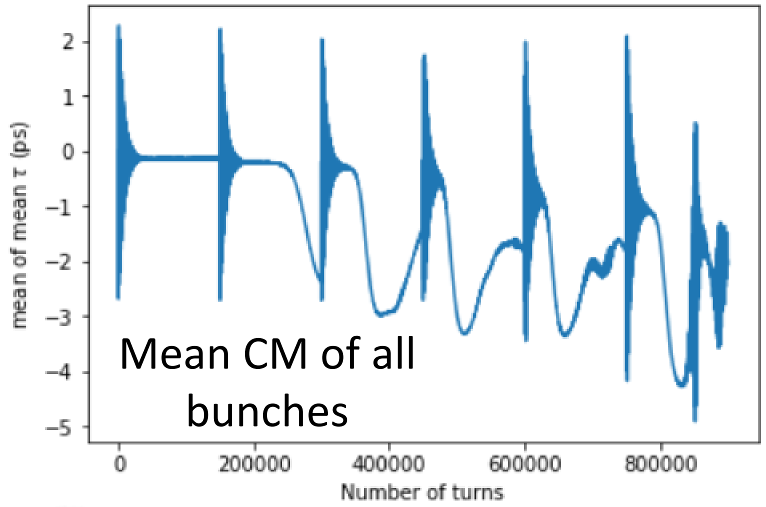
$$\Delta\phi = \frac{2\pi\mu}{M} \approx 300°$$

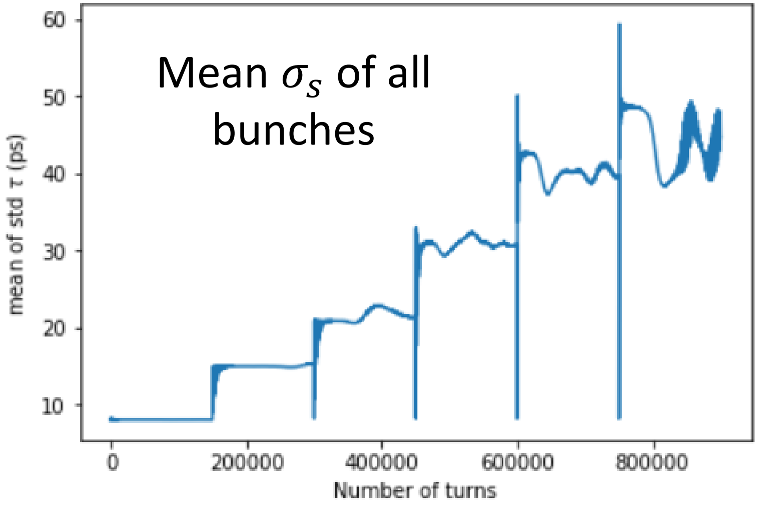
$$6 \times \Delta\Phi\ \%\ 360 = 0$$

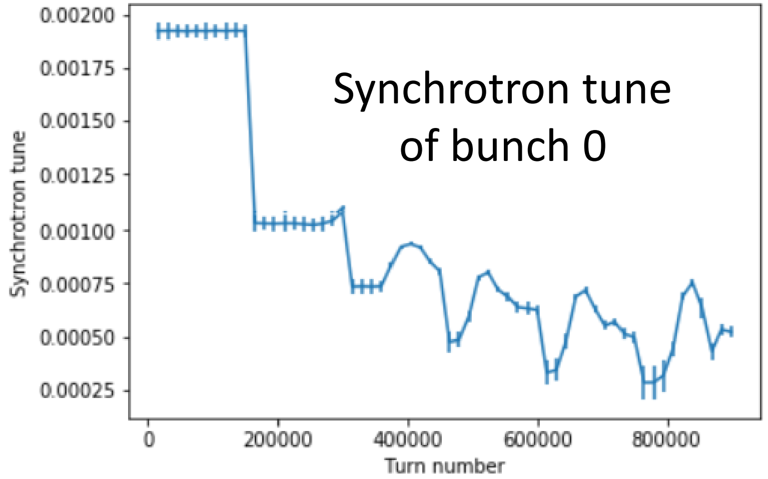
HOM instability w/ harmonic cavity

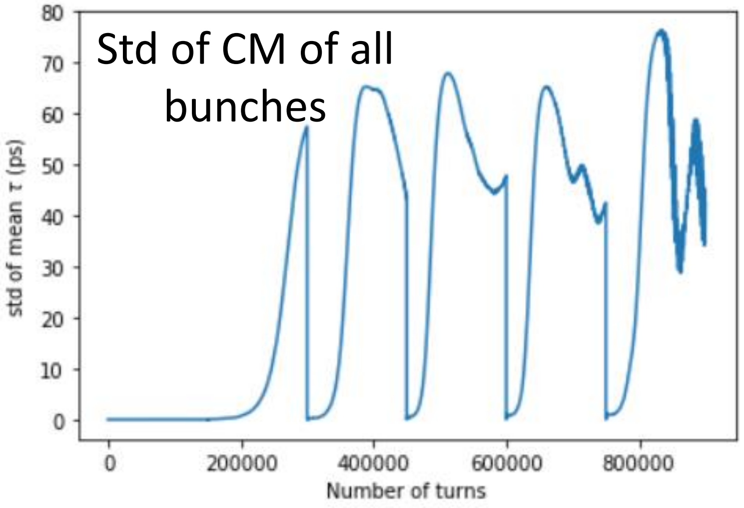
Now including the 3rd harmonic cavity with a HOM setting which was stable without the HC.
Scanning the tunning of the HC from 10 000 kHz to 83 kHz :

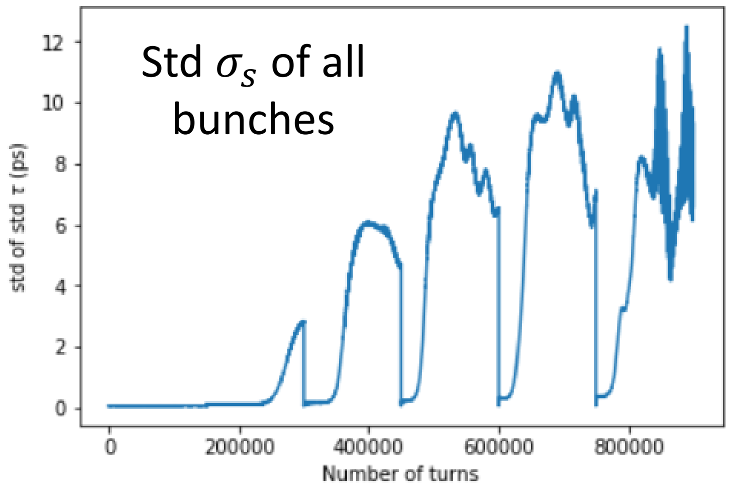
Case : $R_s = 10\ k\Omega$
$\mathbf{Q = 100}$

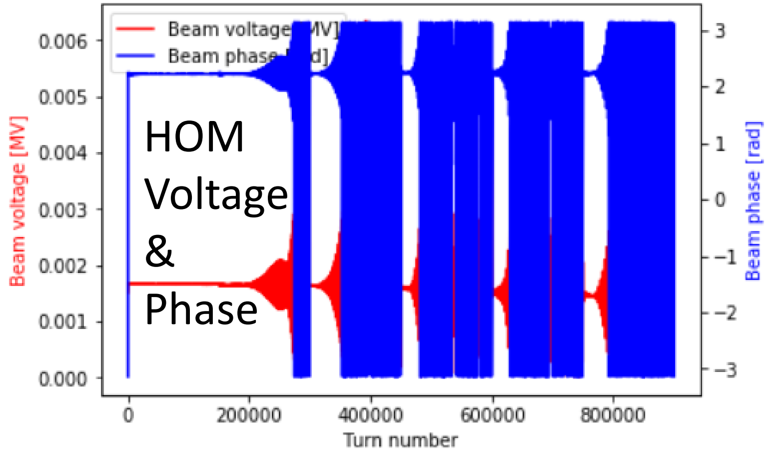




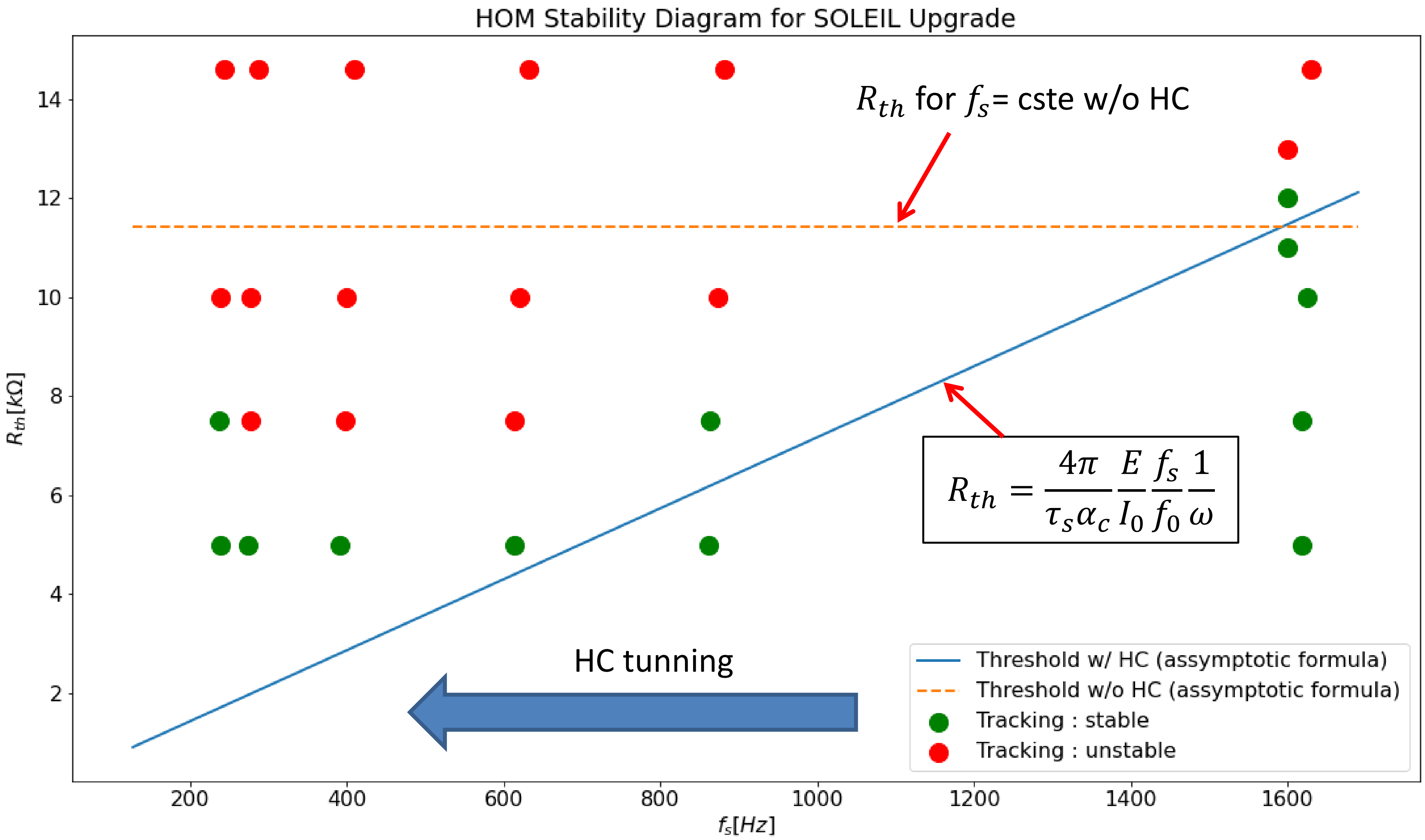








HOM Stability Diagram



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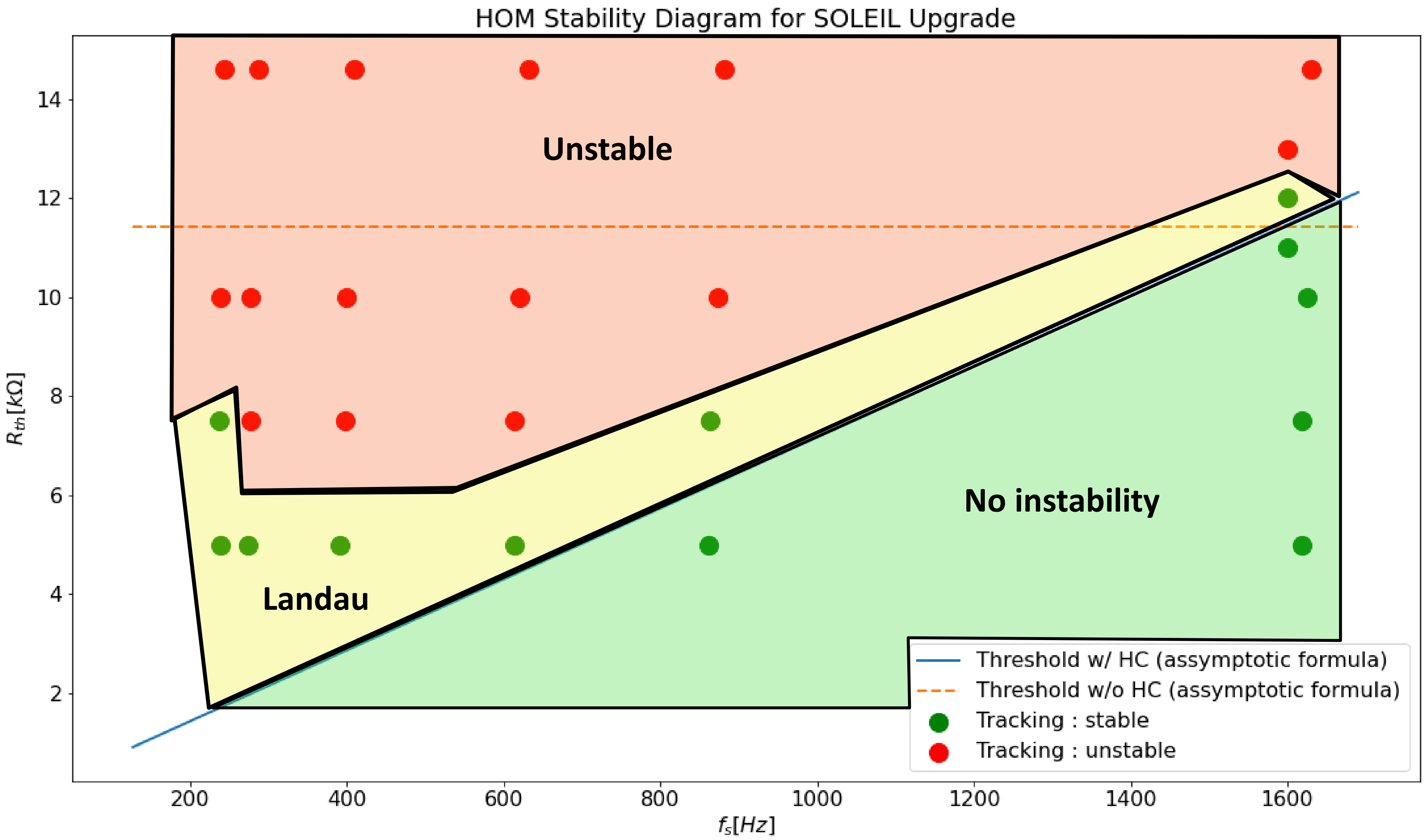
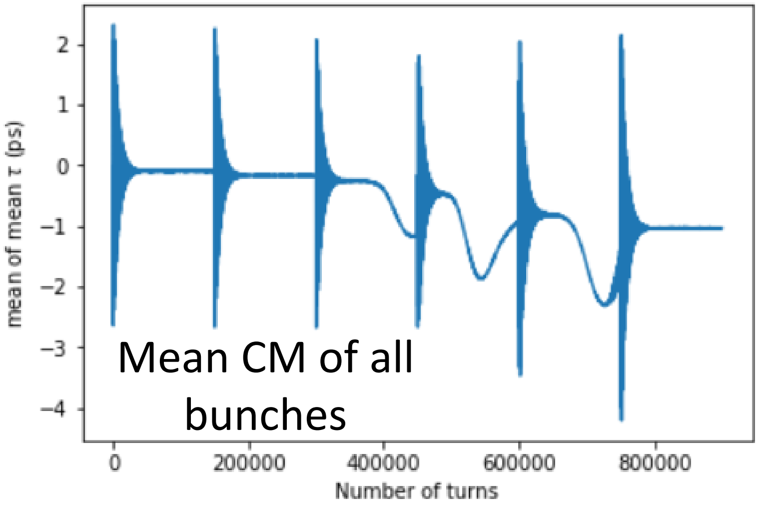
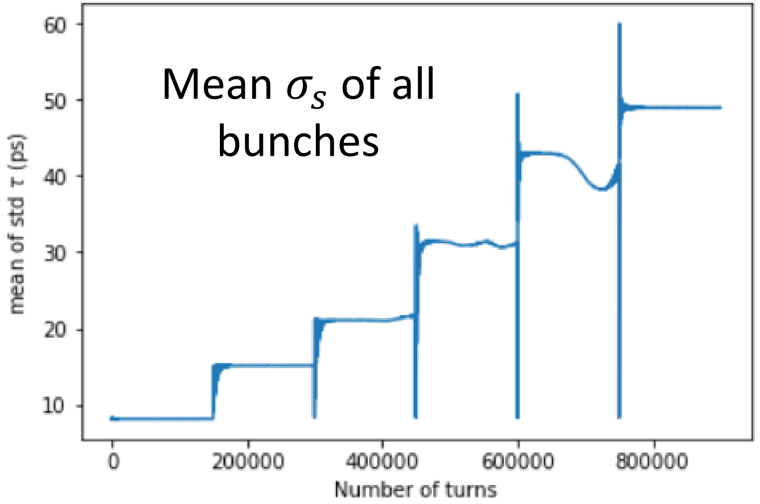


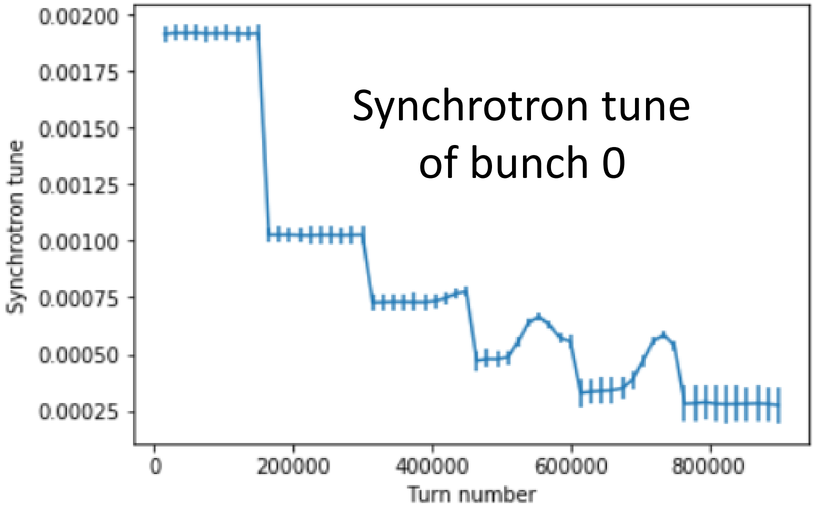
Landau damping of HOM instability

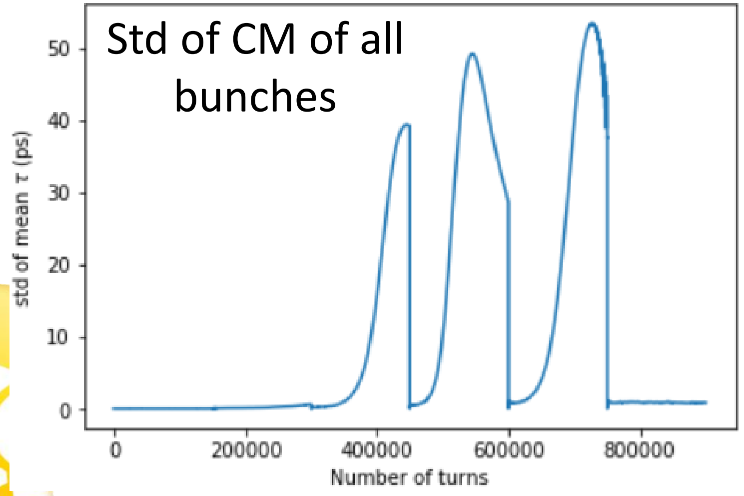
The effect of the Landau damping is quite clearly shown here as the suppression of the instability by the tune spread induced by the HC for the last step of the scan.

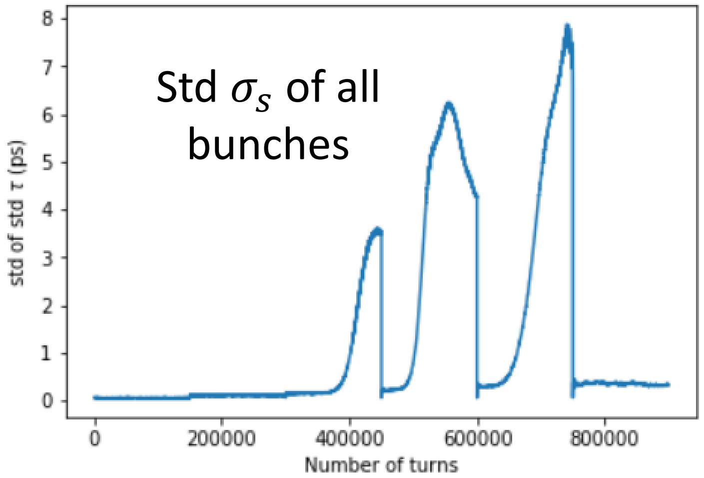
Case : $R_s = 7,5\ k\Omega$
$\mathrm{Q} = 100$

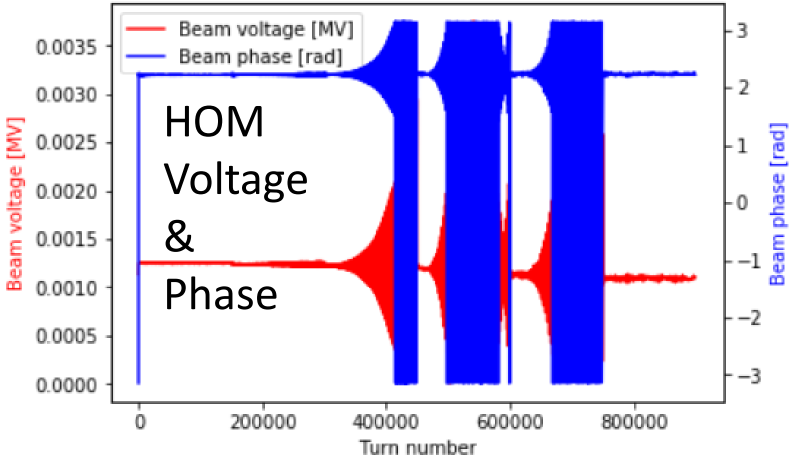












HOM instability for SOLEIL Upgrade

- The shunt impedance of HOM at 1,7 GHz in ESRF type cavities is about $3{,}6\ k\Omega$ per cavity (4 cavities in total).
- Without HC, the threshold is between $12\ k\Omega$ and $13\ k\Omega$. So at least 3 or 4 cavities needs to be at the resonance to trigger this instability.
- Outside the resonance, the Q of this HOM increases rather quickly the threshold.
- With the HC tuned in, the threshold is reduced is between $5\ k\Omega$ and $7{,}5\ k\Omega$. So, two cavities at the resonance could trigger this instability (or even one cavity if the shunt impedance is much bigger than simulated).
- The probability of triggering this instability should be investigated by Monte Carlo simulations considering an error model of the HOMs.
- We are still considering different mitigation strategies to cure this instability if needed (longitudinal feedback, temperature tuning, …).

Comments and conclusion

- The RF system with NC MC and SC passive 3rd HC seems to provide the needed bunch lengthening and lifetime for SOLEIL Upgrade (from very low currents ~20/30 mA).

- But it is quite sensible to beam loading. To keep good performances, we will need a gap smaller than 10 bunches and to decrease bunch to bunch current variations.

- HOM instability:
  1. the APS-U staff (discussion w/ L. Emery and R. Lindberg at last IPAC) is also expecting to see an increase of the growth rate by a factor 2 or 3 due to the HC. They have designed a longitudinal feedback specifically to deal with this issue.
  2. Factor 2 increase in growth rate expected in ALS-U (talk of M. Venturini at IPAC)