Collective effects studies for the SOLEIL Upgrade

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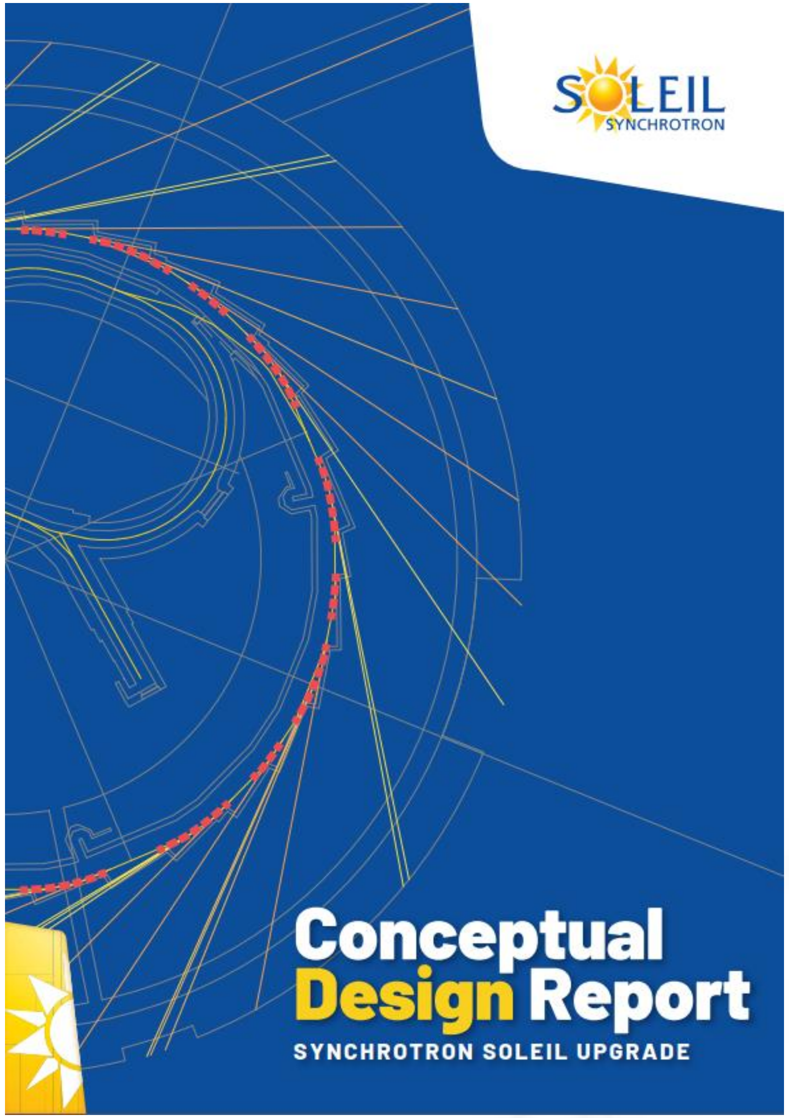
Extreme Storage Ring Workshop (ESRW22)
01/02/2022

SOLEIL Upgrade CDR

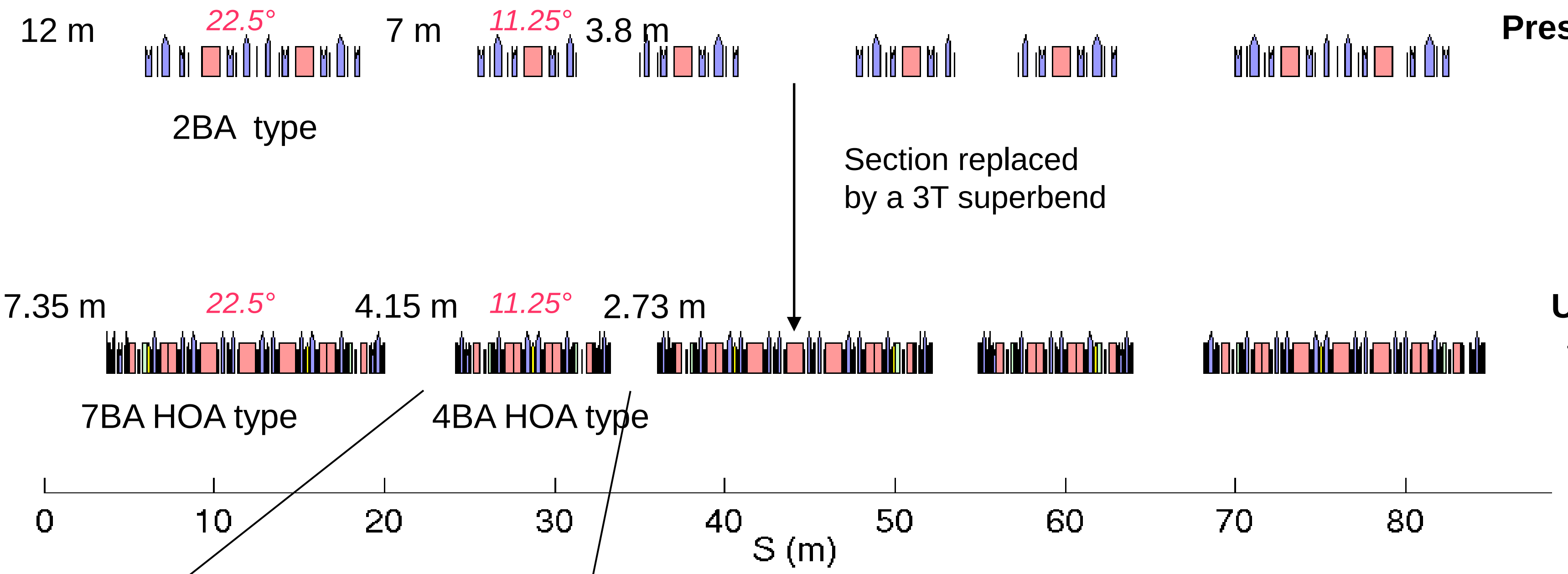
The SOLEIL upgrade conceptual design report has been released in 2021.

In this talk I will only introduce the SOLEIL upgrade lattice very briefly. Detailed information can be found in the CDR document:

https://www.synchrotron-soleil.fr/en/news/conceptual-design-report-soleil-upgrade



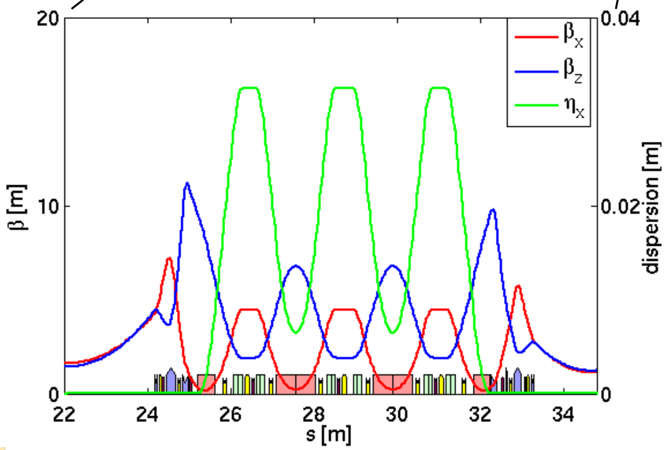
SOLEIL Upgrade CDR lattice



Section replaced by a 3T superbend

Present lattice at 4 nm.rad [32 dipoles]
40 % of straigth length

Upgrade at **80 pm.rad** [126 dipoles]
+reverse-bend to lower the emittance
24 % of straight length



$$\beta_x \sim 1\ m$$

$$\beta_z \sim 1.5\ m$$

	Present lattice	CDR reference lattice
Lattice type	modified DBA	MBA (7BA-4BA)
Circumference (m)	354.10	353.74
Electron beam energy (GeV)	2.75	2.75
Maximum electron beam current (mA)	500	500
Natural emittance (pm.rad)	4000	80
Energy spread (%)	1.16	0.9
Energy loss per turn w/o IDs (keV)	917	490

Why 7BA-4BA ?

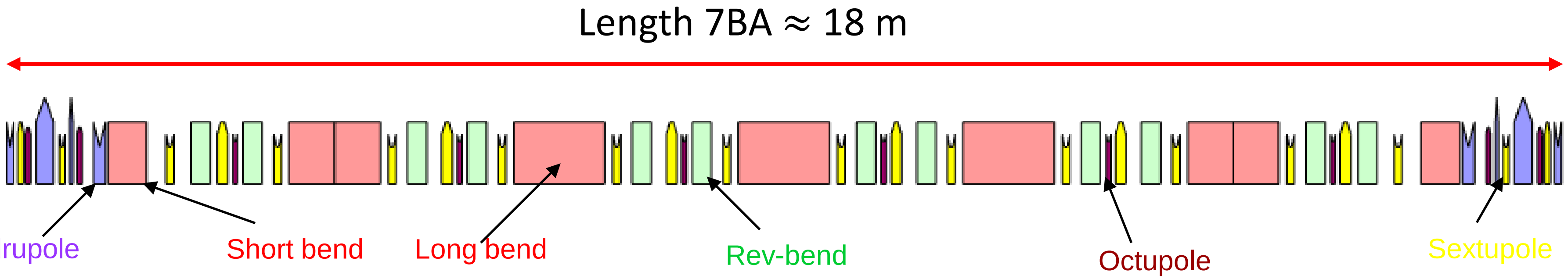
The natural lattice option was to mix ESRF-EBS 7BA cell and the split variation (DIAMOND) 6BA cell having a short straight at center:

- The natural horizontal emittance was considered too large with about 220 pm.rad
- To fit the beamline positioning, the short section had to be reduced below 2 m

Solution :

- To reduce further the emittance : increase the number of cells from 16 to 20
- To fit “at best” the beamlines positioning : alternate 4BA and 7BA HOA type cell (MAXIV and SLS2)

Extreme Storage Ring ?



Permanent magnet
Bore radius = 16 mm
B’ = 110 T/m

Permanent magnet
Bore gap = 24 mm
Short : 1 T & -8 T/m
Long : 0.7 T & -16 T/m

Permanent magnet
Bore radius = 21 mm
B’ = 83 T/m
B = -0.2 T
Quadrupole shifted by 3.8 mm

Electro magnet
Bore radius = 16 mm
1/6 B’’’ = 300000 T/m^3

Electro magnet
Bore radius = 16 mm
1/2 B’’ = 8000 T/m^2

Total number of magnets = 996
(w/o correctors)
Present lattice ≈ 300

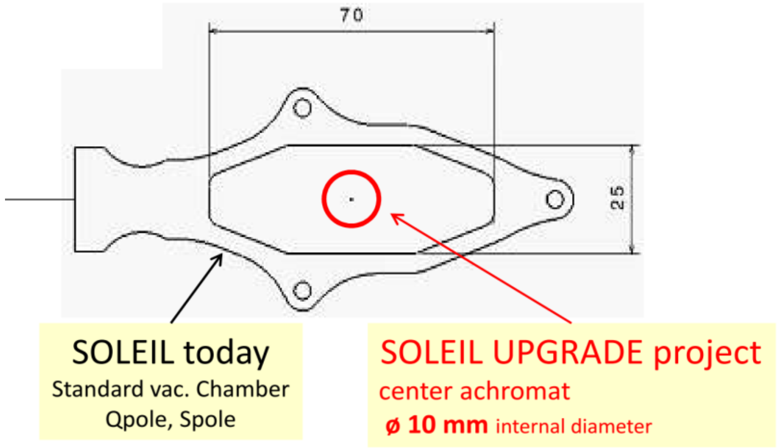
With 2 mm gap and 1 mm pipe width, **the inner pipe diameter is then of 10 mm which is maybe the smallest envisaged in synchrotrons:**

- Standard ion pumps are mostly ineffective so 95 % of the ring should be NEG coated.
- Power extraction is very challenging
- High resistive wall impedance contribution

$$Z_{\parallel,RW} \propto \frac{1}{r\sqrt{\sigma}} \qquad Z_{\perp,RW} \propto \frac{1}{r^3\sqrt{\sigma}}$$

Beam pipe radius

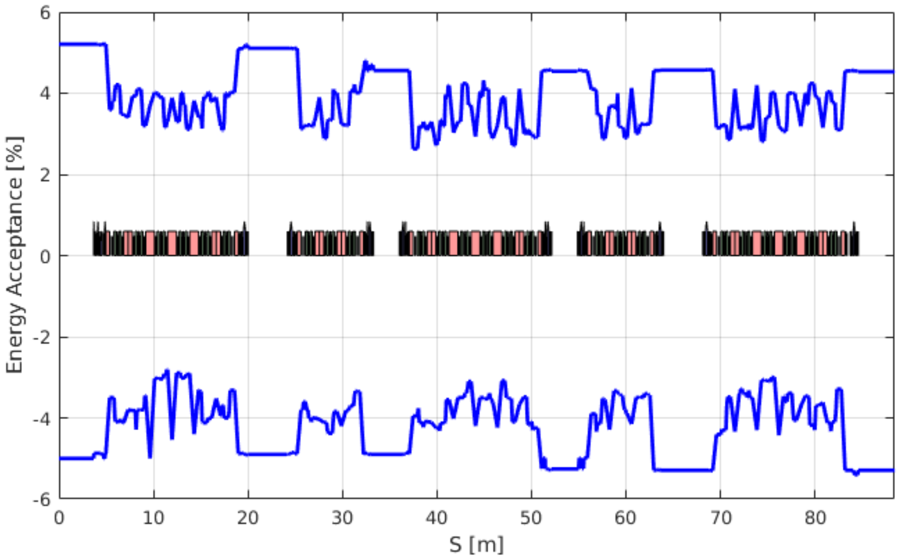
Conductivity

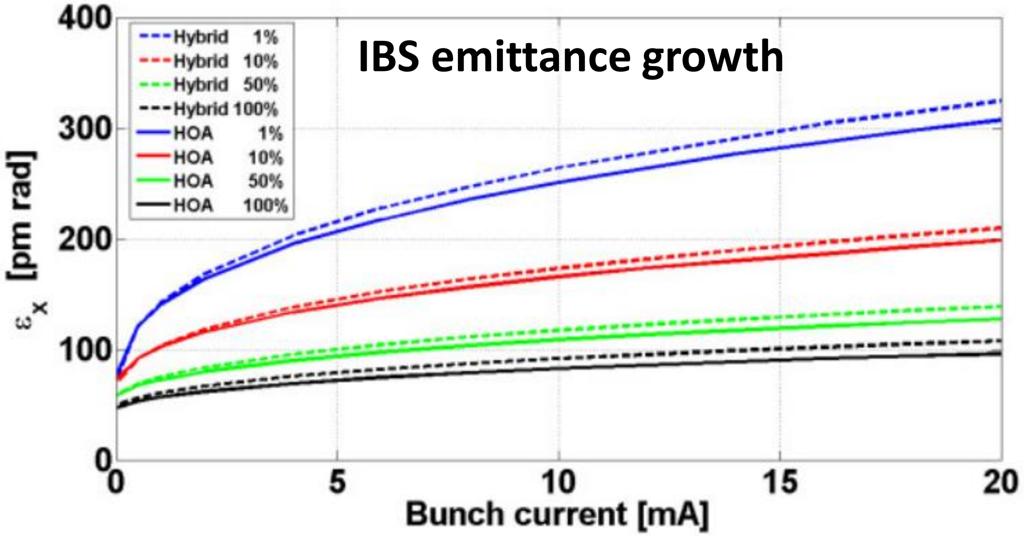


SOLEIL today
Standard vac. Chamber
Qpole, Spole

SOLEIL UPGRADE project
center achromat
ø 10 mm internal diameter

Extreme Storage Ring ?




IBS emittance growth

For the uniform filling mode at 500 mA (1.2 mA per bunch) and using 10% of coupling:

- Typical Touschek beam lifetime is ~**1.4 hrs** with a perfect lattice.
- Intra beam scattering (IBS) induce an **emittance growth from 80 pm.rad to about 100 pm.rad**.

It is essential to lengthen the bunches to be able to mitigate these effects. **The idea is to use a super conducting passive HC of the 3rd or 4th harmonic.**

This talk will be about the consequences of this lattice design on the collective effects:

- Longitudinal beam dynamics with bunch lengthening
- Collective effects with extremely small beam pipe aperture $r \approx 5$ mm

Condition for bunch lengthening

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

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

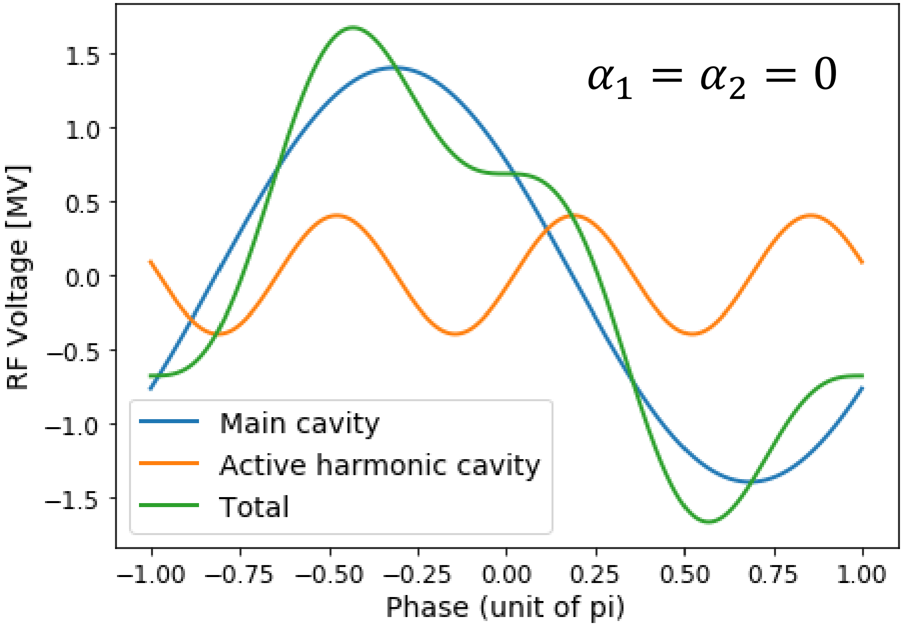
Voltage and phase of the main cavity

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:

$$\cos(\phi_1) = \frac{m^2}{m^2-1}\frac{U_{loss}}{eV_1} \qquad \tan(\phi_2) = \frac{(V_1\omega_{RF}\sin(\phi_1) - \alpha_1)\, m}{V_1\omega_{RF}\cos(\phi_1)} \qquad V_2 = -\frac{V_1\cos(\phi_1)}{m^2\cos(\phi_2)}$$

(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)

$$V(t) = -2I_0R_s\,\mathrm{F}\cos(\psi)\cos(m\omega_{RF}t + \psi - \Phi)$$

Beam current

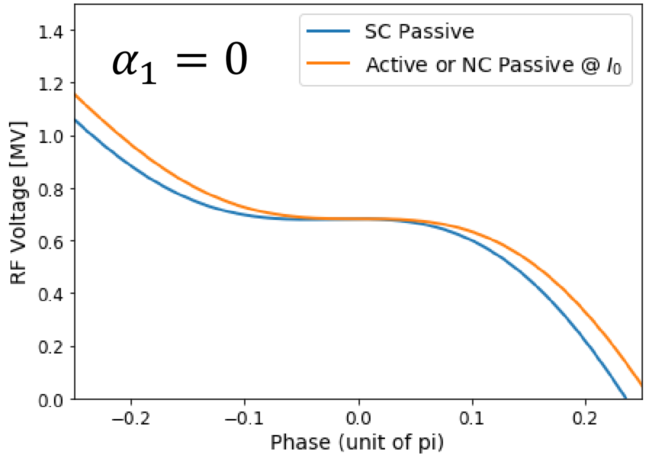
Cavity shunt impedance

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

Cavity detuning

$$\tan(\psi) = Q\left(\frac{\omega_r}{m\omega_{RF}} - \frac{m\omega_{RF}}{\omega_r}\right) \approx 2Q\frac{\Delta\omega}{\omega_r}$$

Cavity quality factor

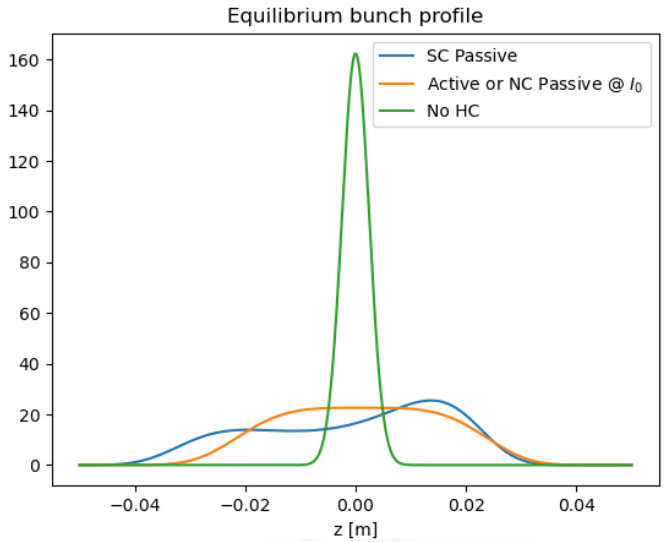


For a chosen beam current I_0 and shunt impedance R_s, conditions to get the “flat potential” are very similar to the active case:

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

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

$$V_2 = -\frac{V_1\cos(\phi_1)}{m^2\cos(\psi)^2} = -2I_0R_s$$



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” anymore.

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

(passive) Harmonic cavity

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 $\frac{d^2V_{tot}}{dt^2} = 0$. The advantage is that you can use the SC HC from much lower current compared to a NC HC.

If you assume small oscillations ($\tau \approx 0$) in the longitudinal equation of motions with a double RF system, you can write the linear synchrotron frequency as:

$$\omega_s^2 = \frac{e\eta\omega_{RF}}{E_0 T_0}[1-\xi]V_1 \sin(\phi_1) \qquad \text{where} \qquad \xi = -\frac{mV_2 \sin(\phi_2)}{V_1 \sin(\phi_1)} \underset{\nwarrow}{=} \frac{2mI_0R_sFcos(\psi)\sin(\psi-\Phi)}{V_1 \sin(\phi_1)}$$

Passive HC case

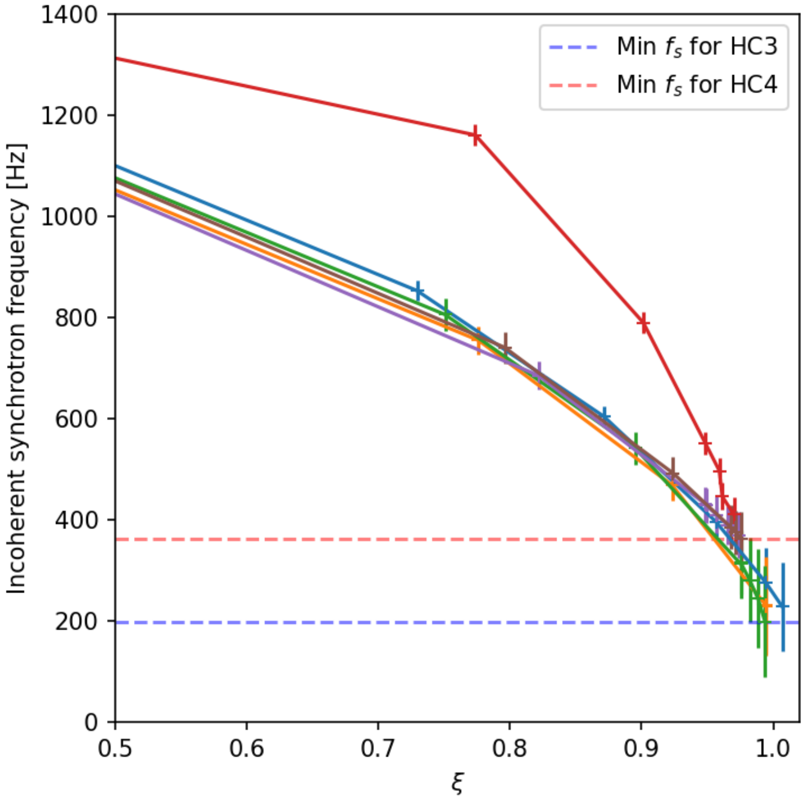
$\xi = 0$ corresponds to the usual case without harmonic cavity and $\xi = 1$ corresponds to the “flat potential conditions”

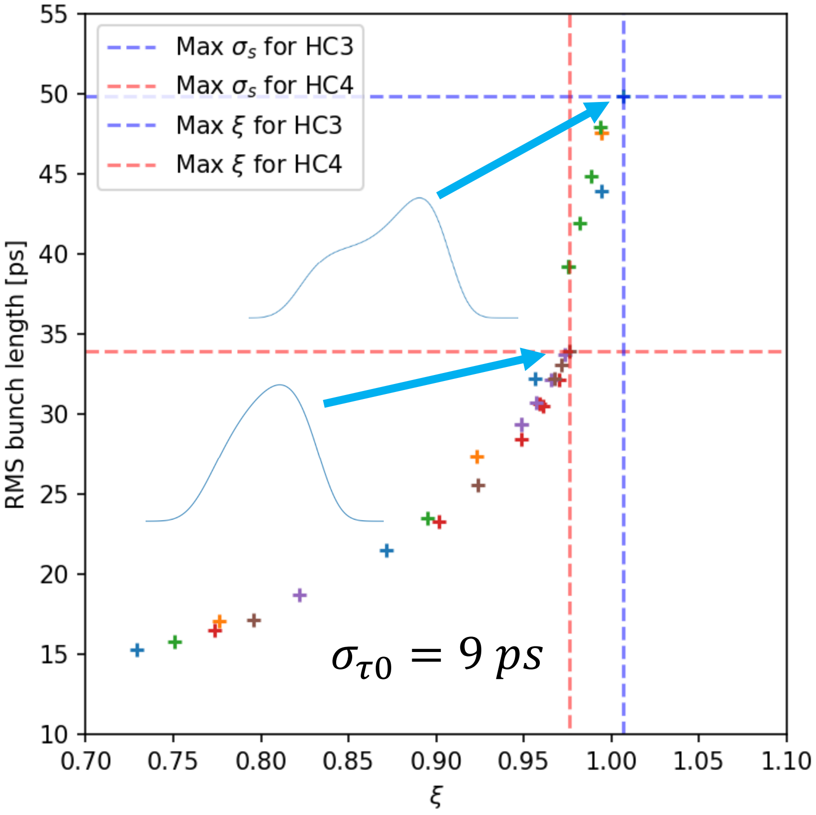
The matching condition gives you an estimate of the expected bunch lengthening: $\sigma_\tau = \frac{\alpha_c \sigma_\delta}{\omega_s}$

Bunch lengthening at high current (500 mA)

Things get interesting when the double RF system is pushed close (or beyond) $\xi = 1$ to get an important bunch lengthening factor.

Here are the stable settings found for a 3rd HC and a 4th HC for the SOLEIL Upgrade using multi-bunch tracking taking into account the beam loading in the main and harmonic cavity (mbtrack2):





At high current, 500 mA in uniform filling, the 3rd HC allows to get a bit past “flat potential conditions” while the 4th HC is limited before $\xi = 1$.

The limitation, in both cases, is the “slow moving transient instability” but it is happening at different distance from the “flat potential conditions”.

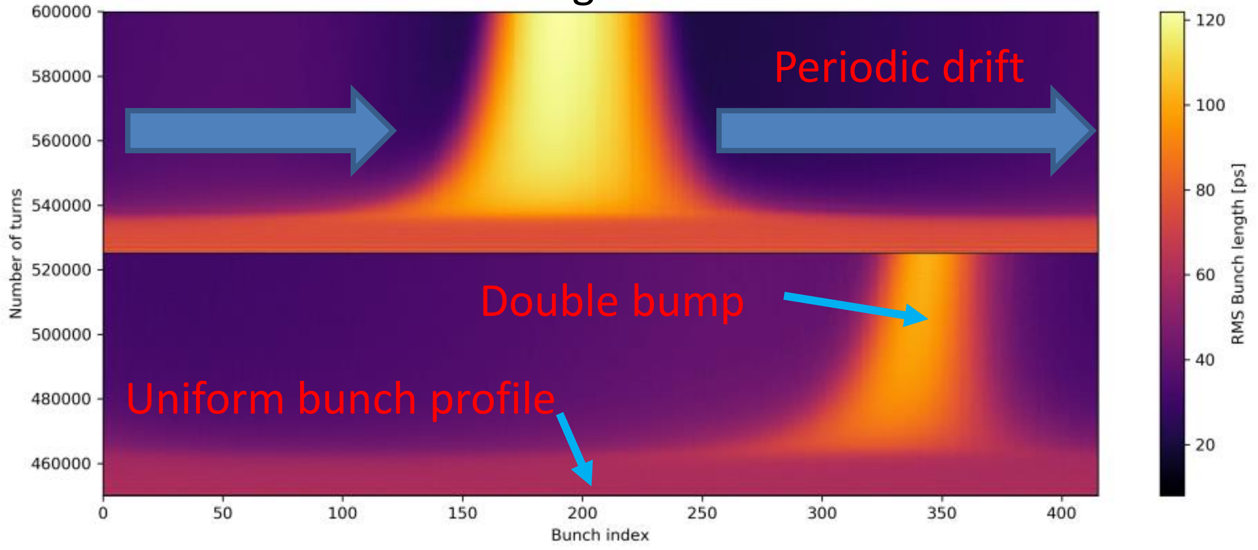
Slow moving transient instability

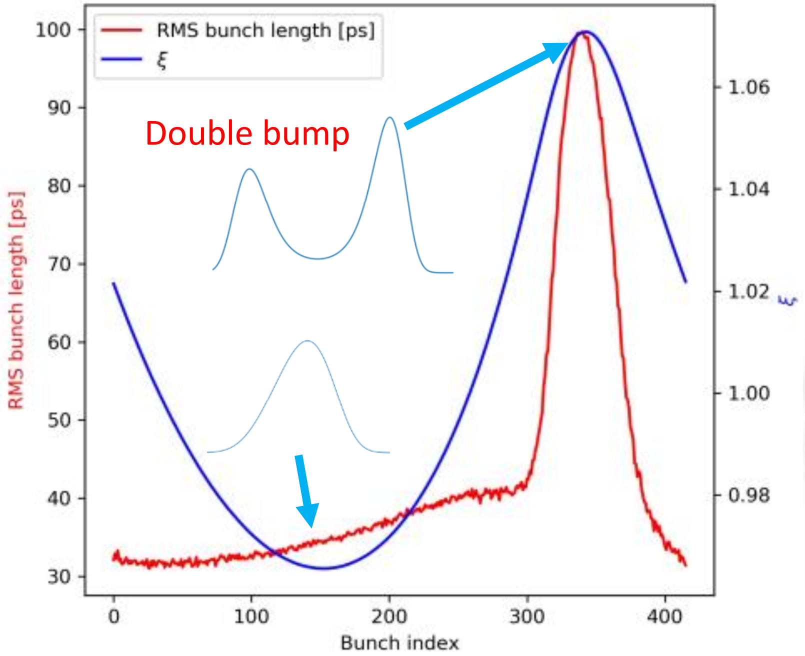
This “slow moving transient instability” seems to happen when the usual stable solution found in the case of a uniform filling beam where all the bunches have the same bunch profile break down:

- When $\xi \ll 1$, all the bunches have the same behavior as the conditions set for the RF system allow for a solution for a set of equation (energy balance condition, form factor equations for both MC and HC) with a unique bunch profile ρ_0.
- When getting close to the $\xi = 1$ condition, this solution for a unique bunch profile for all the bunches no longer exists which “forces” the different bunches to have different bunch profiles. In that case, the system fall back to a very different state where a quasi-stable state is found. This quasi-stable state can drift slowly in the bunch index space with a rather long time period (f ≈Hz).

It has been observed in simulations (SOLEIL-U, Diamond-II) and experimentally at MAX IV[1] and has yet to be fully understood.

RMS bunch length vs bunch index





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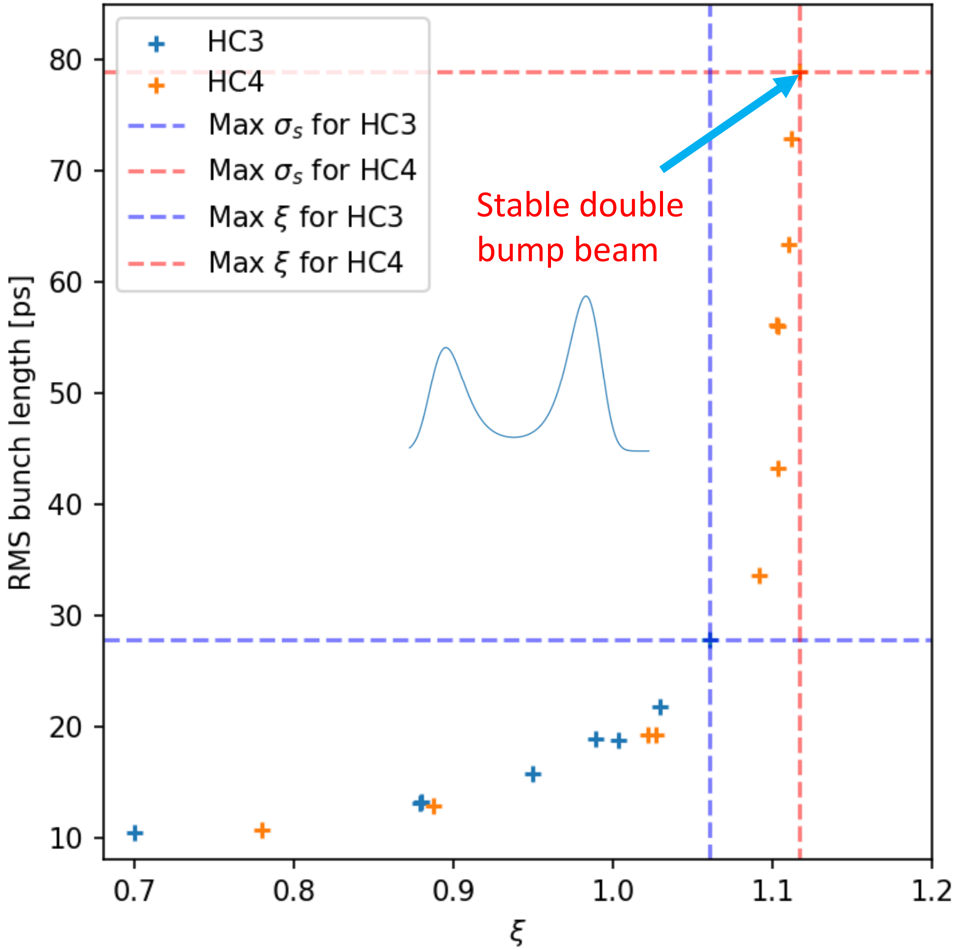
[1] Private communication with T. Olson (Diamond) and F. Cullinan (MAXIV).

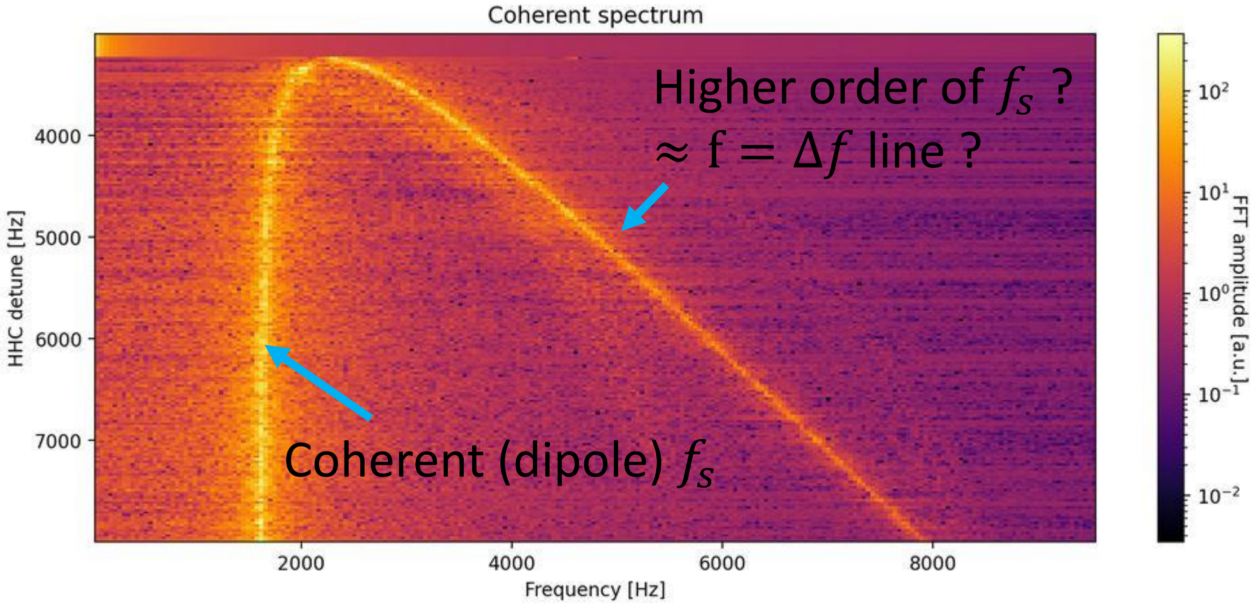
Bunch lengthening at low current (20 mA)

We also want to have the possibility to lengthen the bunches at low current, for example for the single bunch mode (at 20 mA) where the Touschek lifetime and IBS are very critical.



Stable double bump beam

In that case, the picture is very different as the 4th HC allow to lengthen the bunches all the way to double bump bunches in a stable way.
The 3rd HC is very rapidly limited by another instability which could be the "fast mode coupling instability" [1] or simply the interaction of cavity detuning with the dipole mode synchrotron frequency (?).



Higher order of f_s ?
$\approx$ f $= \Delta f$ line ?

Coherent (dipole) f_s

[1] R. A. Bosch, K. J. Kleman, and J. J. Bisognano, "Robinson instabilities with a higher-harmonic cavity", Physical Review Special Topics-Accelerators and Beams 4, Publisher: APS, 074401 (2001).

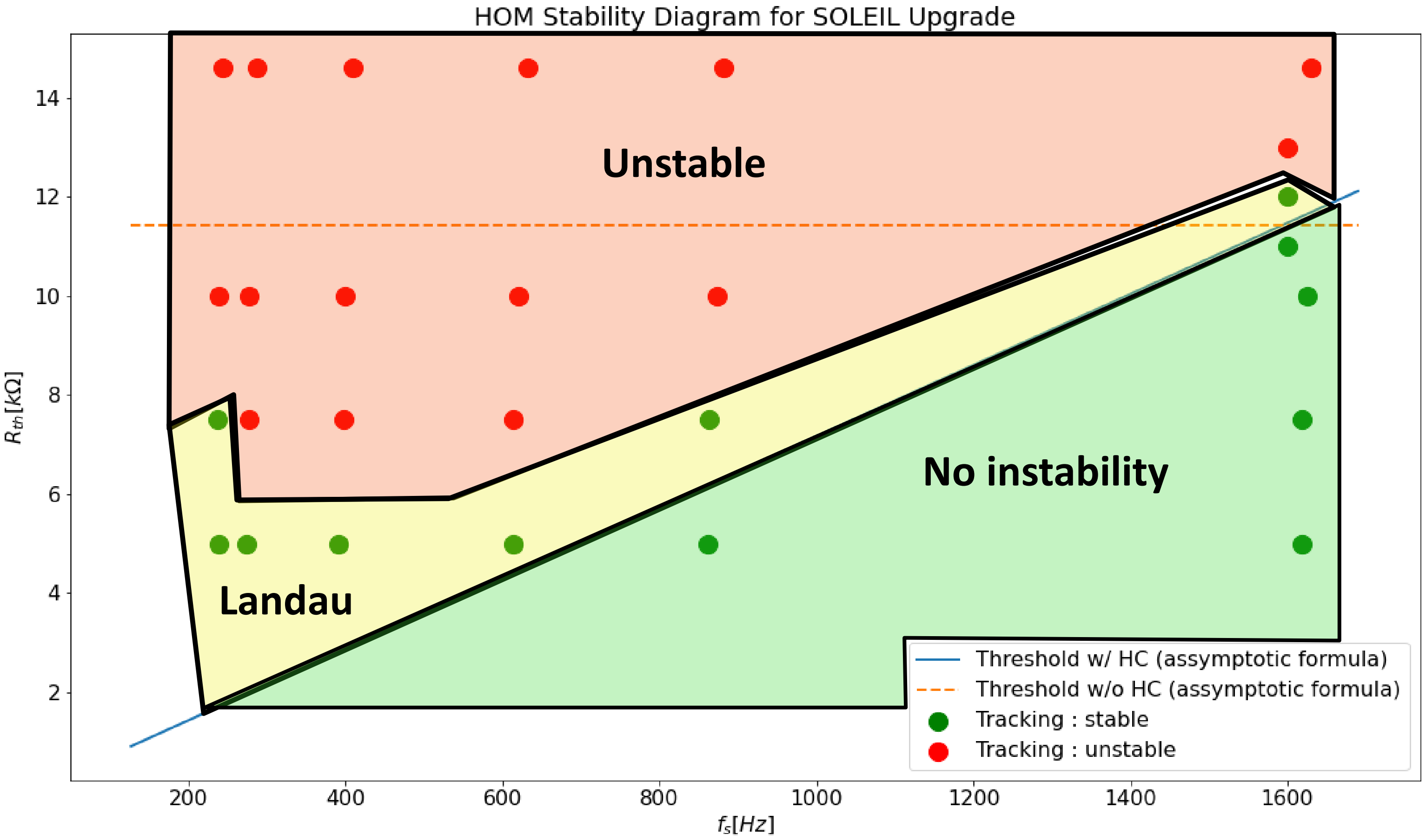
HOM Instability

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:

$$\boxed{R_{th} = \frac{4\pi}{\tau_s \alpha_c} \frac{E}{I_0} \frac{f_s}{f_0} \frac{1}{\omega}}$$

- The lowering of the incoherent synchrotron frequency induced by the harmonic cavity lower the HOM threshold.
- In SOLEIL upgrade case, this effect is not compensated by the increased Landau damping due to the synchrotron frequency spread.



RW induced coupled bunch instability

Effective radius b_{eff} for the resistive wall (RW) impedance:

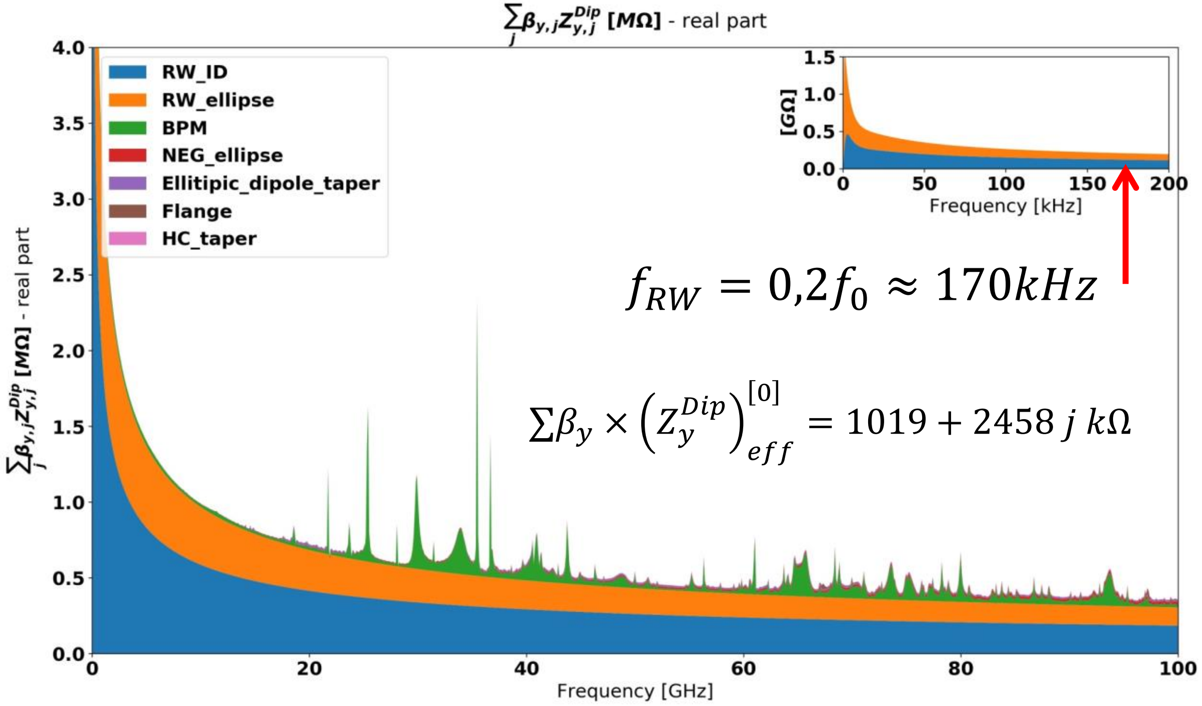
$$b_{eff}^{(n)} = \frac{L\beta^*}{\sqrt{\sigma^*}}\left(\sum_i \frac{l_i\beta_i}{r_i^n\sqrt{\sigma_i}}\right)^{-1} \qquad \sigma^* = \frac{1}{L}\sum l_i\sigma_i \qquad \beta^* = \frac{1}{L}\sum l_i\beta_i$$

$$b_{eff,y} \approx 4\ mm \qquad b_{eff,x} \approx 6\ mm$$

Elements	Length
RW ID (elliptic - 3 mm x 80 mm - Cu)	18 m
RW (elliptic - 10 mm x 12 mm - Cu)	336 m

$$\tau^{-1} = \mathrm{Im}\,\Delta\Omega_0 = \frac{\beta_0\omega_0 I}{4\pi E/e}\frac{R}{b_{\mathrm{eff}}^3}\left[\frac{2cZ_0\rho_r}{(1-\Delta Q_\beta)\omega_0}\right]^{1/2},$$

$$(I_{\mathrm{th}})_{\mathrm{RW}}^{\xi=0} = \frac{4\pi E/e}{c\beta_0}\frac{b_{\mathrm{eff}}^3}{\tau_{\mathrm{rad}}}\left[\frac{(1-\Delta Q_\beta)\omega_0}{2cZ_0\rho_r}\right]^{1/2}.$$



$$f_{RW} = 0{,}2 f_0 \approx 170 kHz$$

$$\sum\beta_y \times \left(Z_y^{Dip}\right)_{eff}^{[0]} = 1019 + 2458\, j\ k\Omega$$

b_{eff}	τ	I_{th}
4 mm	117 µs	6 mA
5 mm	228 µs	12 mA
6 mm	395 µs	21 mA

$$\tau_x = 7{,}3\ ms$$

$$\tau_y = 13{,}1\ ms$$

[1] Nagaoka, R., & Bane, K. L. (2014). Collective effects in a diffraction-limited storage ring. *Journal of synchrotron radiation*.

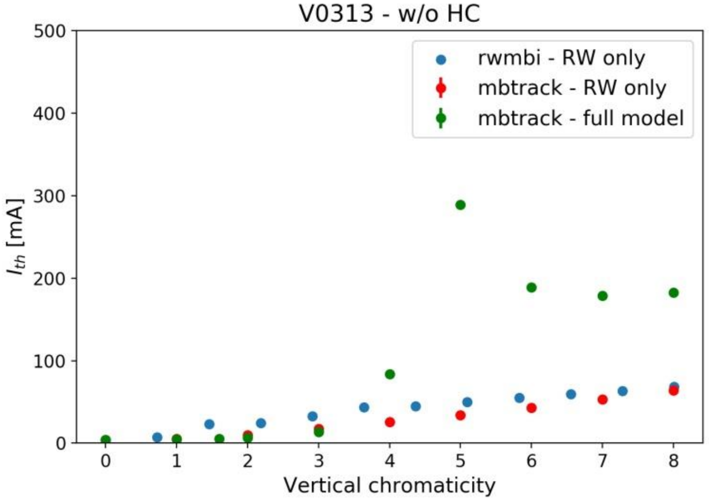
RW induced coupled bunch instability

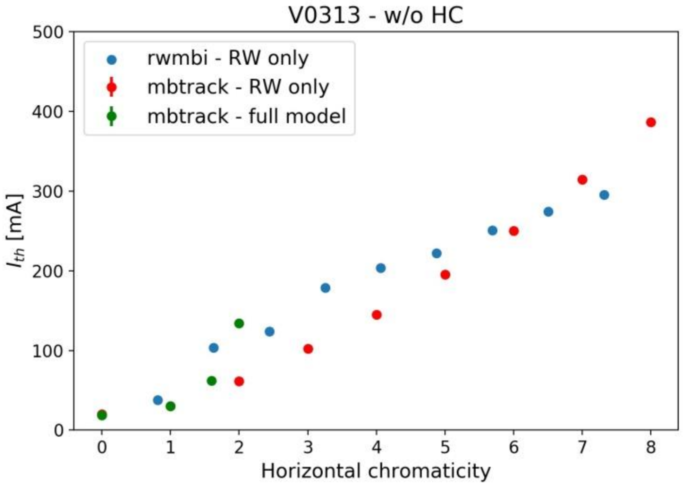
- The RW coupled bunch instability threshold is first estimated by tracking the 416 bunches with 10^6 macro-particles (mbtrack[1]), and then by a Vlasov solver (rwmbi[2]), assuming only the RW impedance with IDs gap closed @ 3 mm:
  - $I_{th,Y} = 5\ mA$ and $I_{th,X} = 20\ mA$ for $\xi_{x,y} = 0$
  - $I_{th,Y} = 10\ mA$ and $I_{th,X} = 65\ mA$ for $\xi_{x,y} = 2$
  - $I_{th,Y} = 35\ mA$ and $I_{th,X} = 195\ mA$ for $\xi_{x,y} = 5$

Good point for a benchmark, as at $\xi = 0$, the instability threshold does not depend on the geometric impedance.

- Then the full impedance model (longitudinal + transverse) is used to take into account the beneficial impact of head-tail damping:
  - $I_{th,Y} = 4\ mA$ and $I_{th,X} = 20\ mA$ for $\xi_{x,y} = 0$
  - $I_{th,Y} = 7\ mA$ and $I_{th,X} = 135\ mA$ for $\xi_{x,y} = 2$
  - $I_{th,Y} = 295\ mA$ and $I_{th,X} > 500\ mA$ for $\xi_{x,y} = 5$

Very low instability threshold around nominal chromaticity but not so much lower than the one measured on SOLEIL at $\xi_y = 0$, $I_{th,Y} = 30\ mA$ (IDs open)





[1] Skripka, Galina, et al. "Simultaneous computation of intrabunch and interbunch collective beam motions in storage rings." *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 806 (2016).

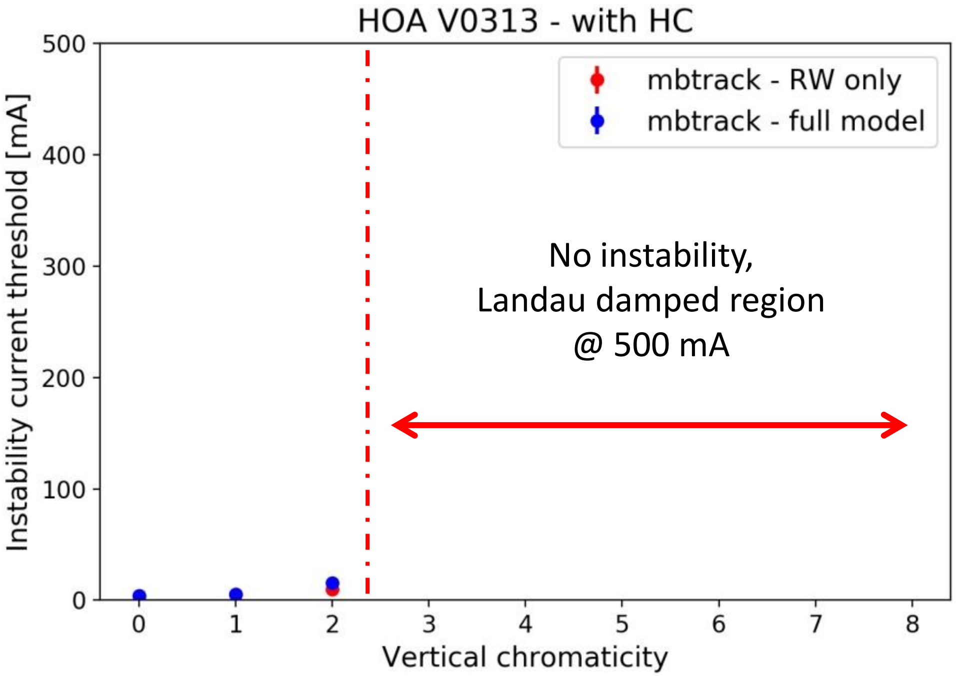
[2] Nagaoka, R., & Bane, K. L. (2014). Collective effects in a diffraction-limited storage ring. *Journal of synchrotron radiation*.

RW induced coupled bunch instability

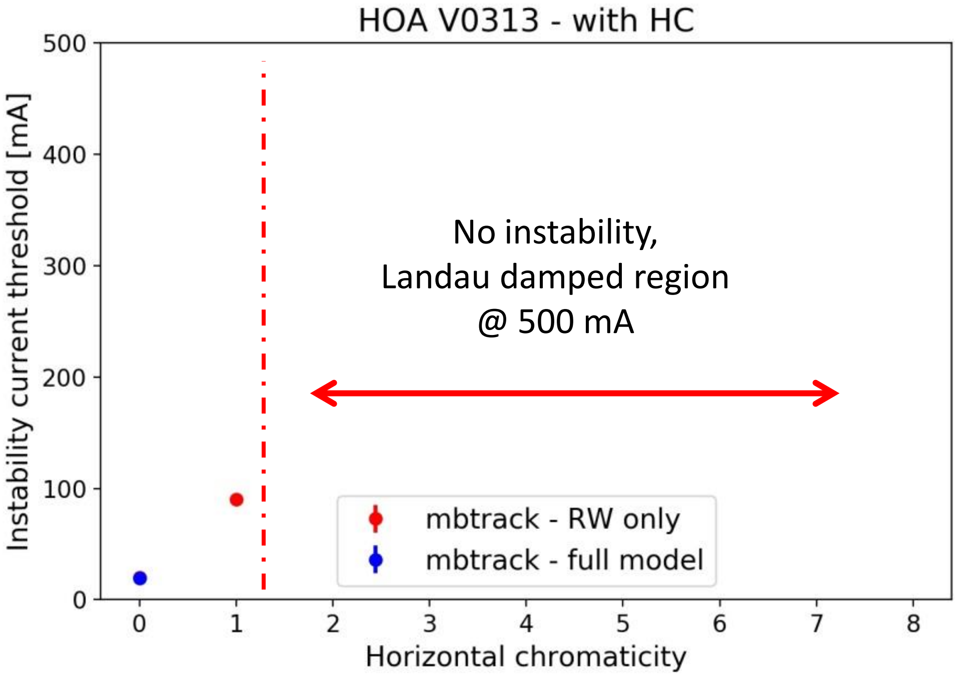
- If the HC (m = 4) is taken into account, the instability is Landau damped by the synchrotron tune spread induced by the HC:
  - $I_{th,Y} = 4\ mA$ and $I_{th,X} = 20\ mA$ for $\xi_{x,y} = 0$
  - $I_{th,Y} = 10\ mA$ and $I_{th,X} > 500\ mA$ for $\xi_{x,y} = 2$
  - $I_{th,Y} > 500\ mA$ and $I_{th,X} > 500\ mA$ for $\xi_{x,y} = 3$

- Only the head-tail modes $m \geq 1$ can be Landau damped by the synchrotron tune spread:

$$\omega_p = \omega_0\left(pM + \mu + k\nu_\beta + m\nu_s\right), \qquad -\infty < p < +\infty, \qquad p \in \mathbb{Z}$$



No instability,
Landau damped region
@ 500 mA



No instability,
Landau damped region
@ 500 mA

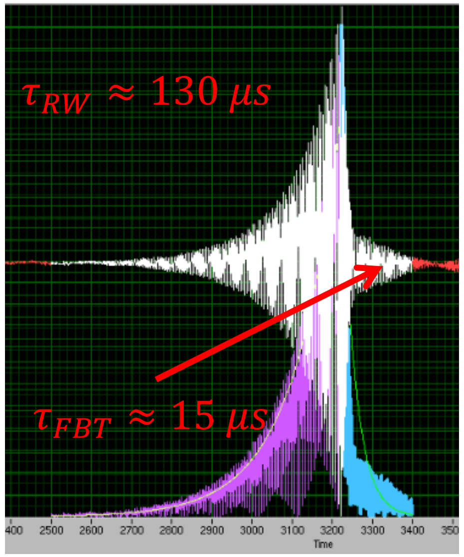
Transverse Feedback & Mitigations

- Transverse Feedback:
  - Has been very effective at SOLEIL and will be improved for the upgrade.
  - Damping time of $\tau_{FBT} \approx 15\ \mu s$ measured at SOLEIL, which is much less than the different expected instability rise times for the upgrade.

- Coupling between the X/Y planes:
  - The synchrotron damping, and thus the instability thresholds, are shared between the two planes when coupling is strong.
  - Landau damping can also be shared on some conditions[1]

- In 4th generation light sources, non-linear effect like the Amplitude Dependent Tune Shift (ADTS) are very strong, but here they are not (yet) taken into account in the simulation. Betatron tune spread can Landau damp the RW mode m = 0 which can not be damped via synchrotron tune spread (HC).

- The synchrotron damping times used to compute the instabilities are the one for the storage ring without the IDs ($U_0 = 490\ keV$), when the IDs are closed the damping times gets smaller ($U_0 \approx 766\ keV$).



Growth-Damp measurement at SOLEIL

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[1] Métral, Elias. "Theory of coupled Landau damping." *Part. Accel.* 62.CERN-PS-99-011-CA (1999).

Thank you for your attention!

Also … two post-doc positions just opened at SOLEIL:

- General beam dynamics and lattice design
- Collective effects

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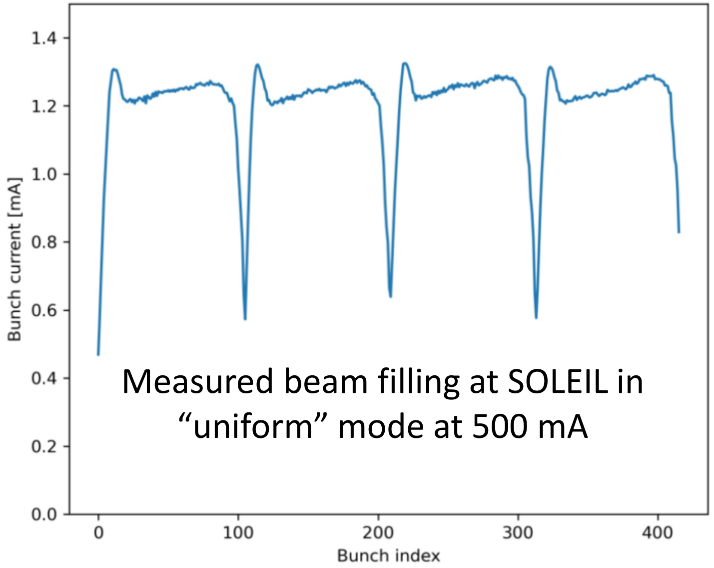
Backup slides

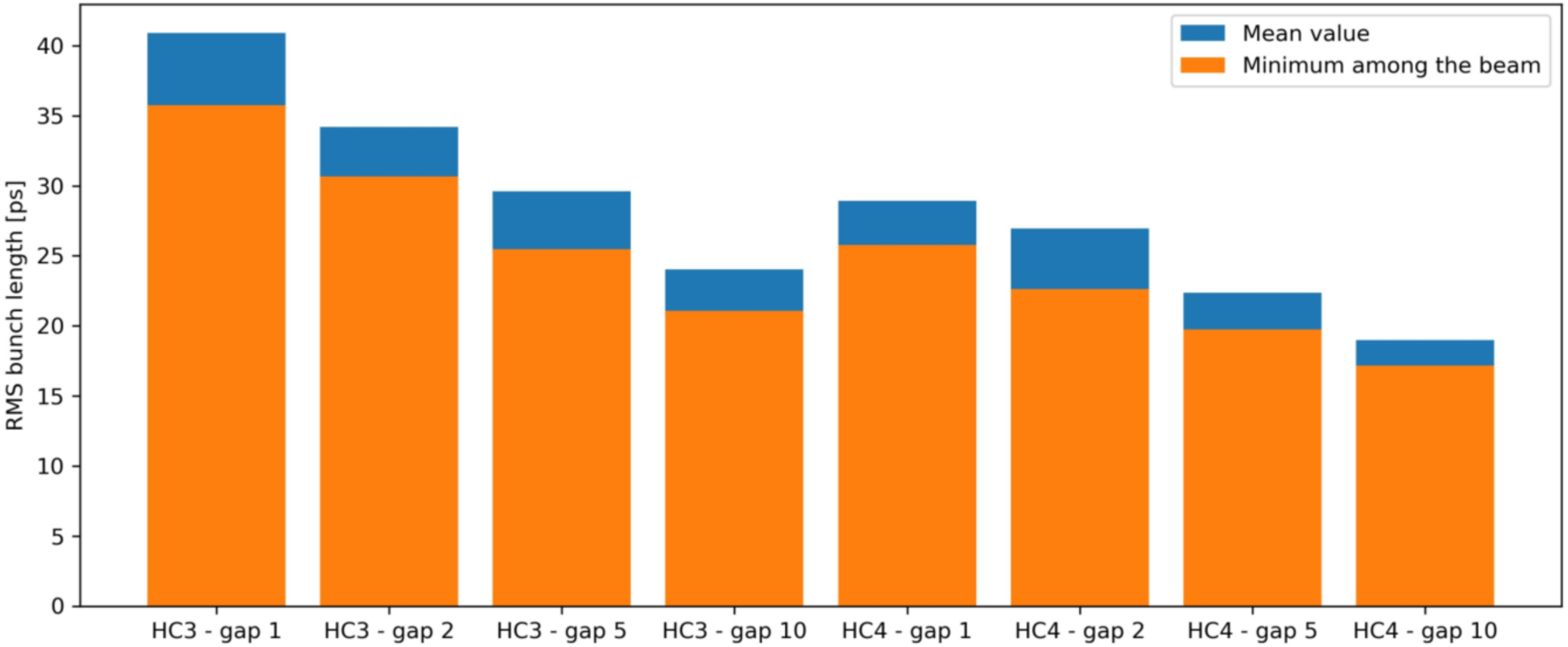
Impact of gaps in the beam filling pattern

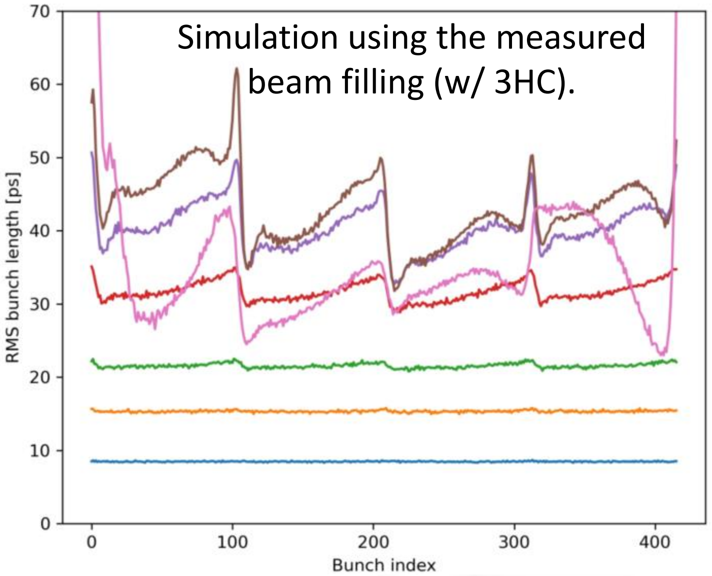
In today SOLEIL, the “uniform” filling pattern is injected by steps of 104 bunches (¼ of the full filling). Due to the transmission from the booster, there is some variation of the current per bunch depending on the bunch index as shown in the **measured filling pattern taken during an operation run**:



Measured beam filling at SOLEIL in “uniform” mode at 500 mA

Impact of gaps in the beam filling pattern

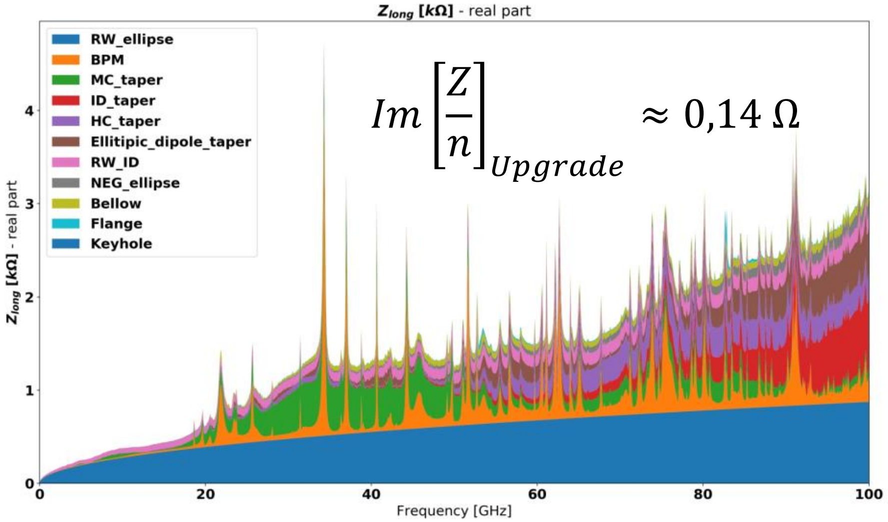




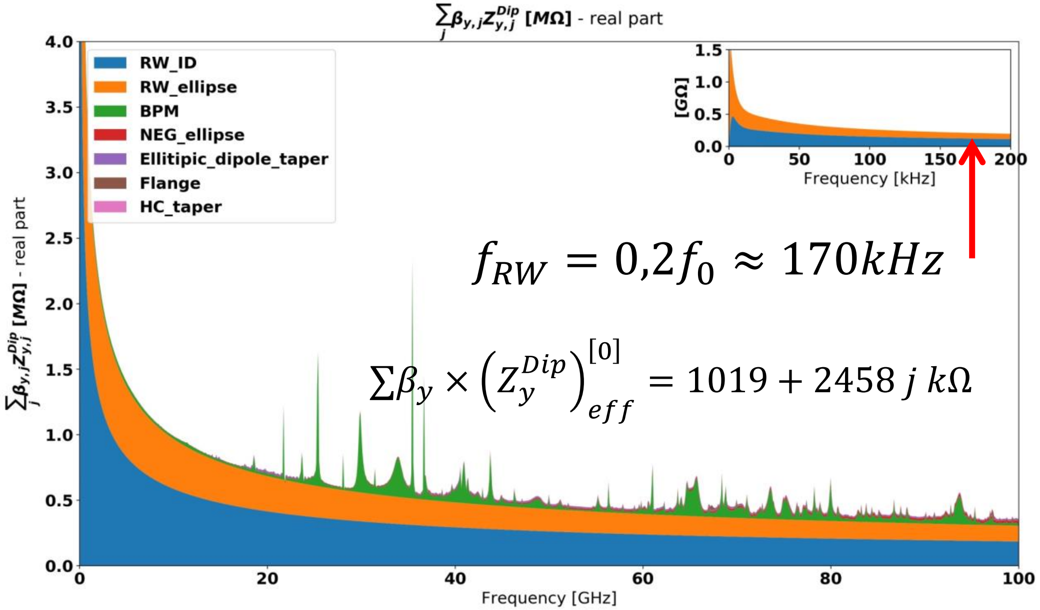
Simulation using the measured beam filling (w/ 3HC).

Impedance model

Elements	Number	Remarks
BPMs	200	
Keyholes	12	
Bellows	125	“comb” type
Flanges	250	“impedance free” type
Taper Main RF (per pair)	1	L = 250 mm ⇔ 10,2°
Taper Harmonic RF (per pair)	1	L = 100 mm ⇔ 8,5°
Taper dipoles (per pair)	116	L = 43 mm ⇔ 8°
Taper ID under vacuum (per pair)	9	L = 100 mm ⇔ 2° (on vertical plane only)
RW ID (elliptic - 3 mm x 80 mm - Cu)	18 m	
RW (elliptic - 10 mm x 12 mm - Cu)	336 m	
NEG	336 m	$\rho_{NEG} \approx 2{,}5 \times 10^{-5} \Omega.m$ $h_{NEG} \approx 1\ \mu m$



$$Im\left[\frac{Z}{n}\right]_{Upgrade} \approx 0{,}14\ \Omega$$

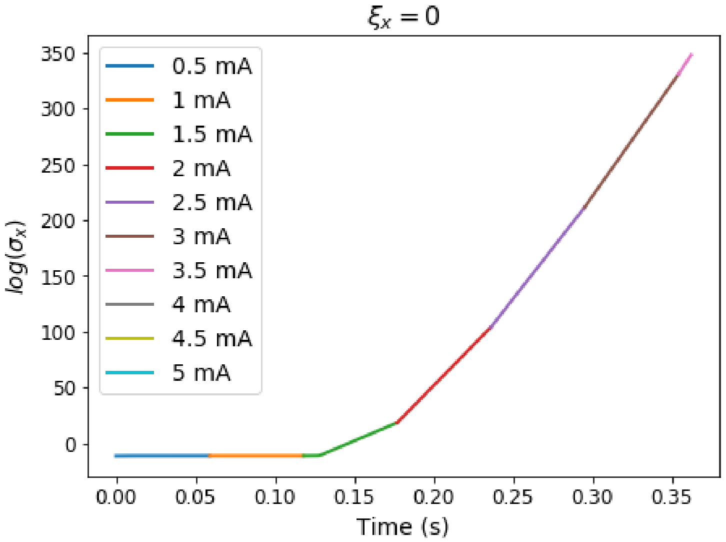


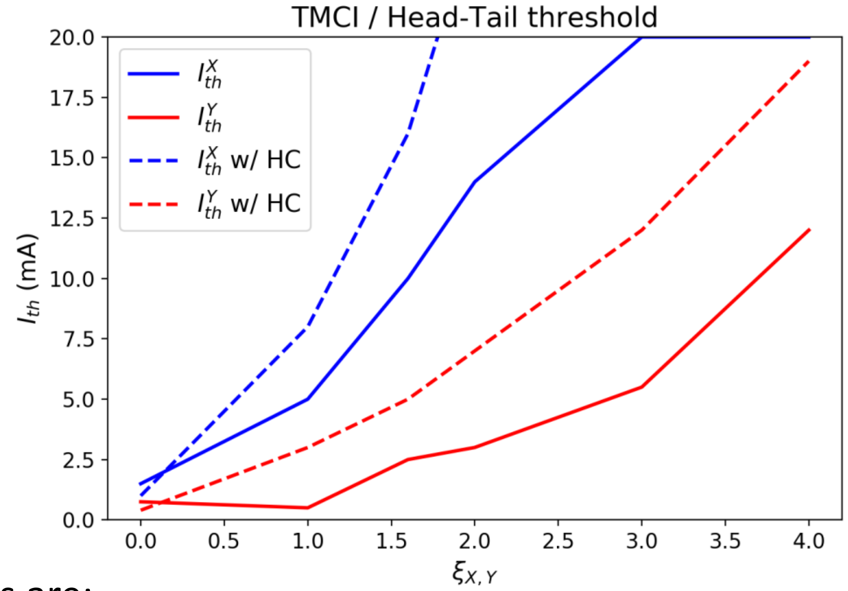
$$f_{RW} = 0{,}2 f_0 \approx 170kHz$$

$$\sum\beta_y \times \left(Z_y^{Dip}\right)_{eff}^{[0]} = 1019 + 2458\ j\ k\Omega$$

TMCI / Head-Tail

The transverse single bunch instabilities, TMCI at $\xi = 0$ and Head-Tail at $\xi \neq 0$, are estimated by using the *mbtrack* tracking code. We take into account both longitudinal and transverse impedances and track 10^6 macro-particles for several damping times.





- For a nominal chromaticity at $\xi_x = \xi_y$ =1,6 the threshold currents are:
  - $I_{th,Y} = 2{,}5\ mA$ and $I_{th,X} = 10\ mA$ without HC
  - $I_{th,Y} = 5\ mA$ and $I_{th,X} = 16\ mA$ with HC (m = 3)

- Recent studies using Vlasov formalism[1] have shown that harmonic cavities (HC) can decrease the TMCI threshold current. Our simulations seems to confirm this prediction.

Because the incoherent synchrotron frequency is much smaller using HC, the mode $l = -1$ is closer to the $l = 0$ mode leading to a decrease of the TMCI threshold.

[1] Venturini, M. "Harmonic cavities and the transverse mode-coupling instability driven by a resistive wall." *Physical Review Accelerators and Beams* 21.2 (2018).

TMCI / Head-Tail

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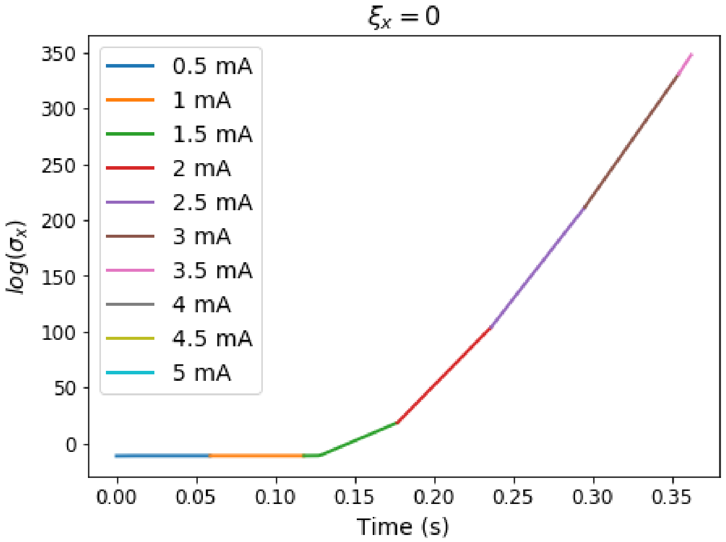

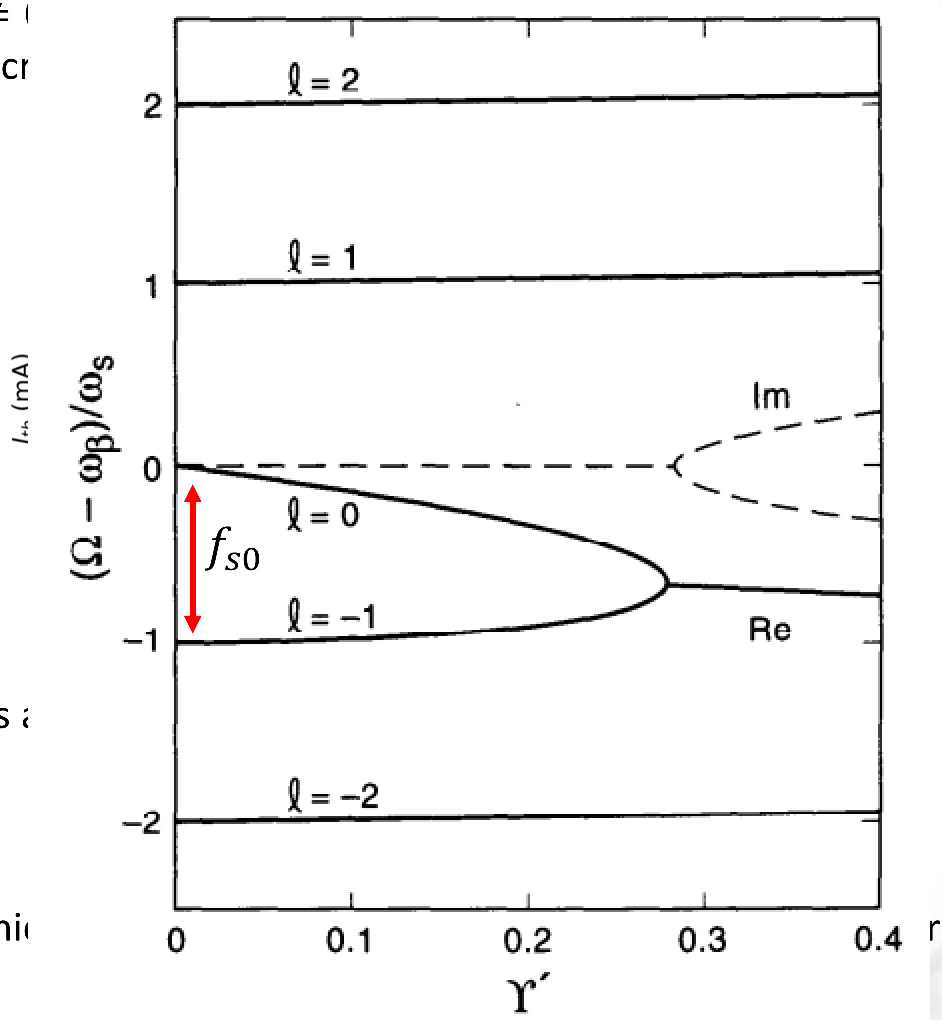

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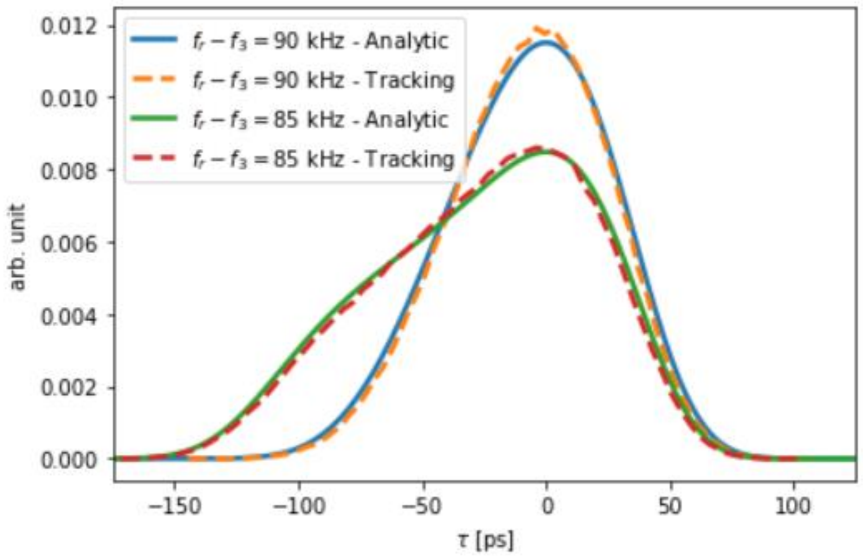
Tools

All the tracking results for harmonic cavities 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.

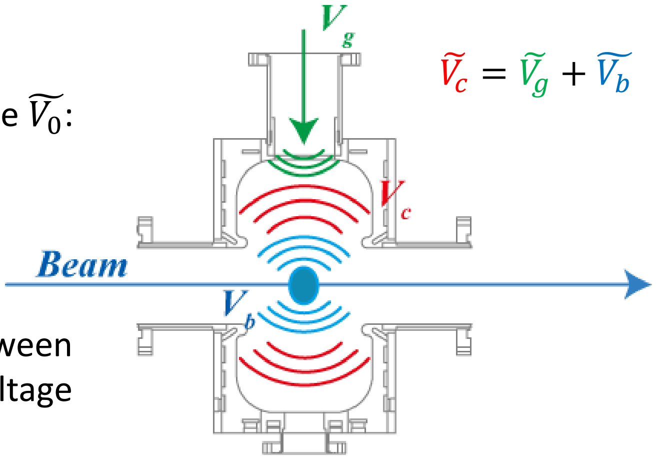
RF Induced Instabilities

- Usual way to include RF systems in macro-particle tracking code, what we call “**perfect cavity**”, 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 $t+\Delta t$ is added to the voltage $\widetilde{V_b}$ already present in the cavity at time t:

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

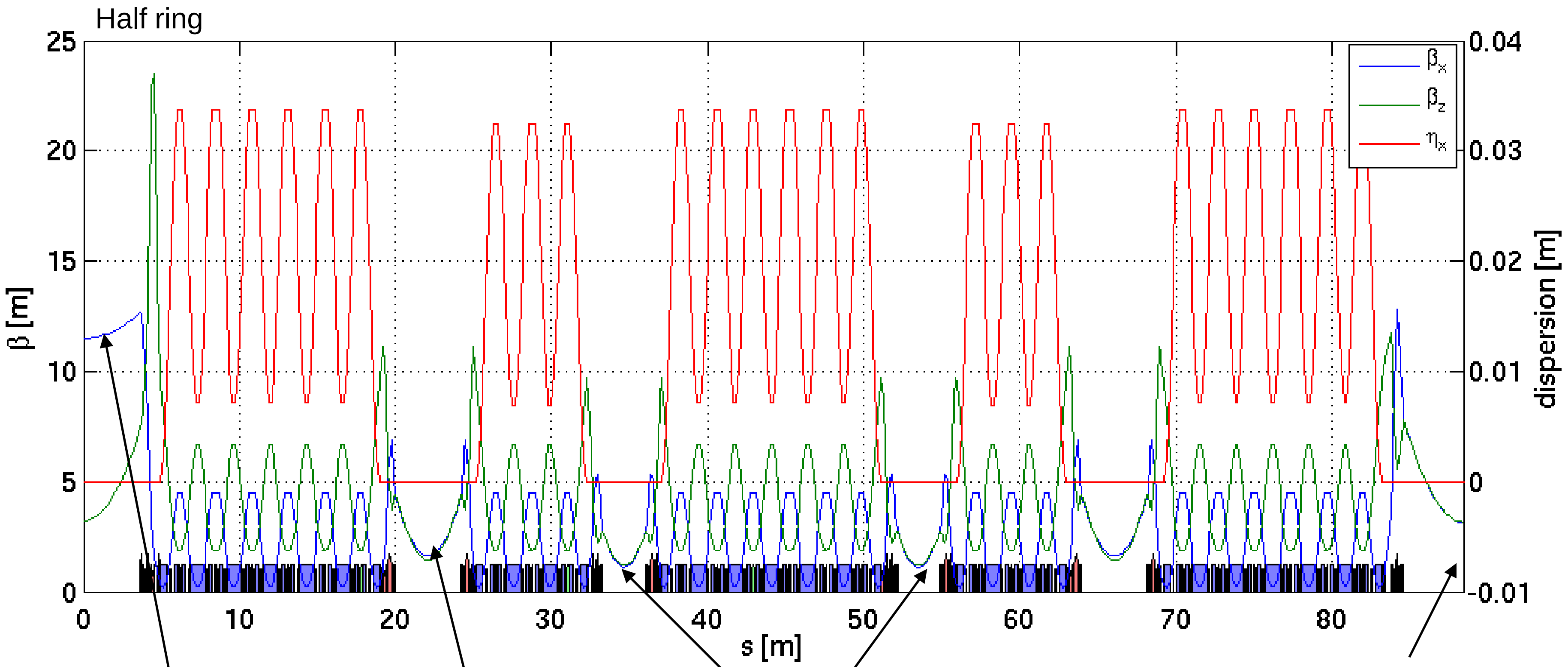
Cavity filling time

Cavity phase slippage

- So the energy change of a particle is given by:

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

Present reference lattice optics : V0313



$Injection$
$\beta_x \sim 11m$
$L = 7.35m$

$\beta \sim 1.5m$
$L = 4.150m$

$\beta \sim 1.1m$
$L = 2.730m$

Chicane and additional triplet of quad to be added here for the canted beamlines

L
$= 7.65m$

RW - Theory

Coupled transverse instabilities occur when certain frequencies of the beam (coherent modes) are excited by their interaction with impedances having neighboring frequencies.

The modes are defined by different numbers, for example for a beam having M bunches:
μ = coupled bunch number = 0, 1, 2, ..., (M - 1)

- m = head-tail number (also called azimuthal or synchrotron) = ..., -2, -1, 0, 1, 2, ...
- k = phase space periodicity number = 1 (dipole), 2 (quadrupole), …

Each mode (m, μ, k) has a frequency spectrum ω_p :

$$\omega_p = \omega_0(pM + \mu + k\nu_\beta + m\nu_s)$$

With p being an integer that can vary between $\pm\infty$, ω_0 is the ring angular revolution frequency, ν_β and ν_s are the betatron and synchrotron tunes.

RW - Theory

For each mode (m, μ), we can compute an effective impedance $(Z_\perp)_{eff}^{[m,\mu]}$ corresponding to the intersection of the impedance $Z_\perp$ with the bunch frequency spectrum h_m sampled at the frequencies ω_p of the mode displaced by the chromatic frequency ω_ξ.

This effective impedance $(Z_\perp)_{eff}^{[m,\mu]}$ can be used to estimate the coherent slip of complex tunes and certain instability thresholds :

$$(Z_\perp)_{eff}^{[m,\mu]} = \frac{\sum_{p=-\infty}^{\infty} Z_\perp(\omega_p) h_m(\omega_p - \omega_\xi)}{\sum_{p=-\infty}^{\infty} h_m(\omega_p - \omega_\xi)}$$

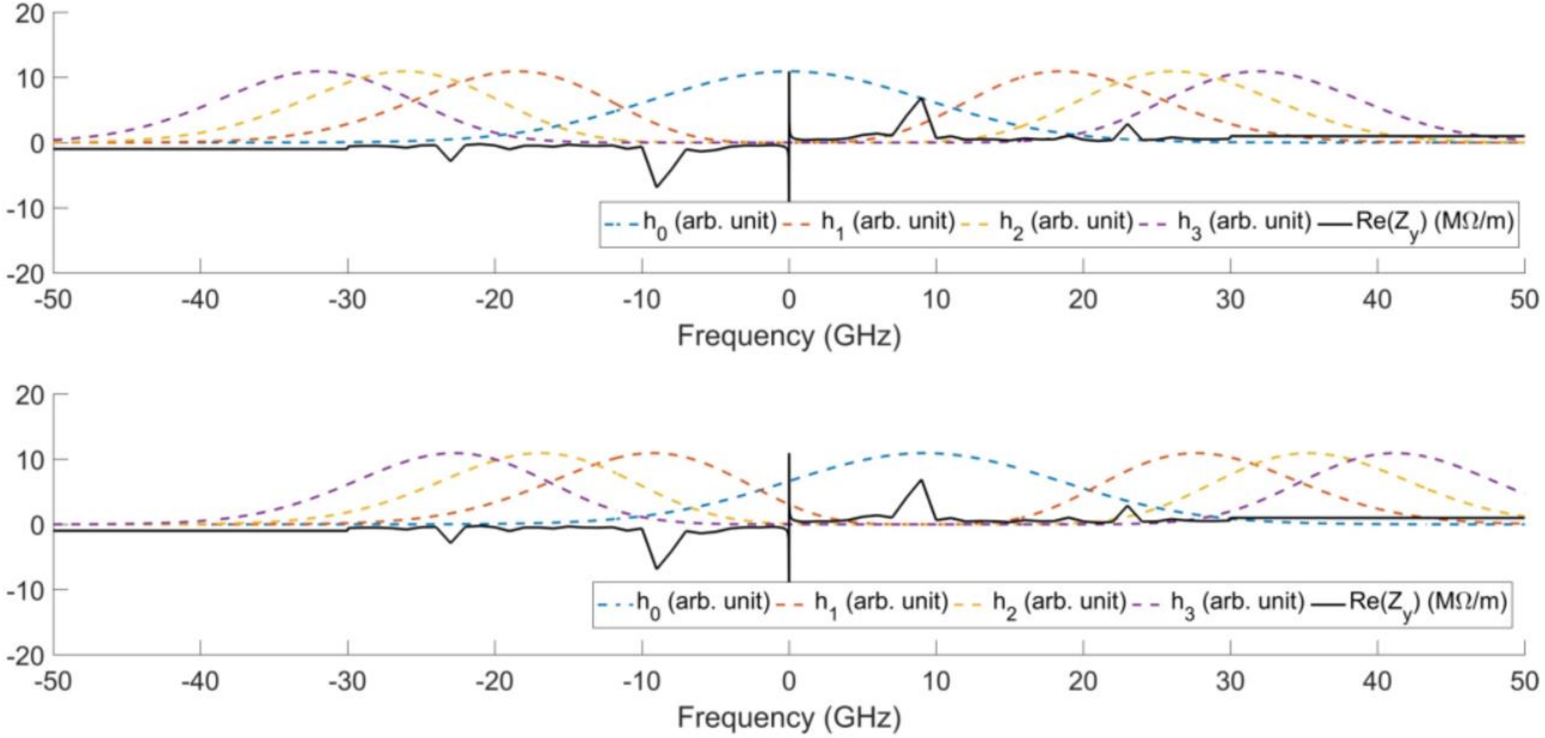
Where $\omega_\xi = \frac{\omega_0 \xi}{\eta}$ is the chromatic frequency which has the effect of shifting in frequency the bunch spectrum h_m, $\xi = \Delta\nu_\beta / \delta$ is the chromaticity (not normalized) and $\eta = \alpha_c - 1/\gamma^2$.

For Gaussian bunch of RMS length σ_s, the bunch frequency spectrum for the m mode is given by:

$$h_m(\omega) = (\omega\sigma_s)^{2m} e^{-\omega^2\,\sigma_s^2}$$

(Hermitian mode)

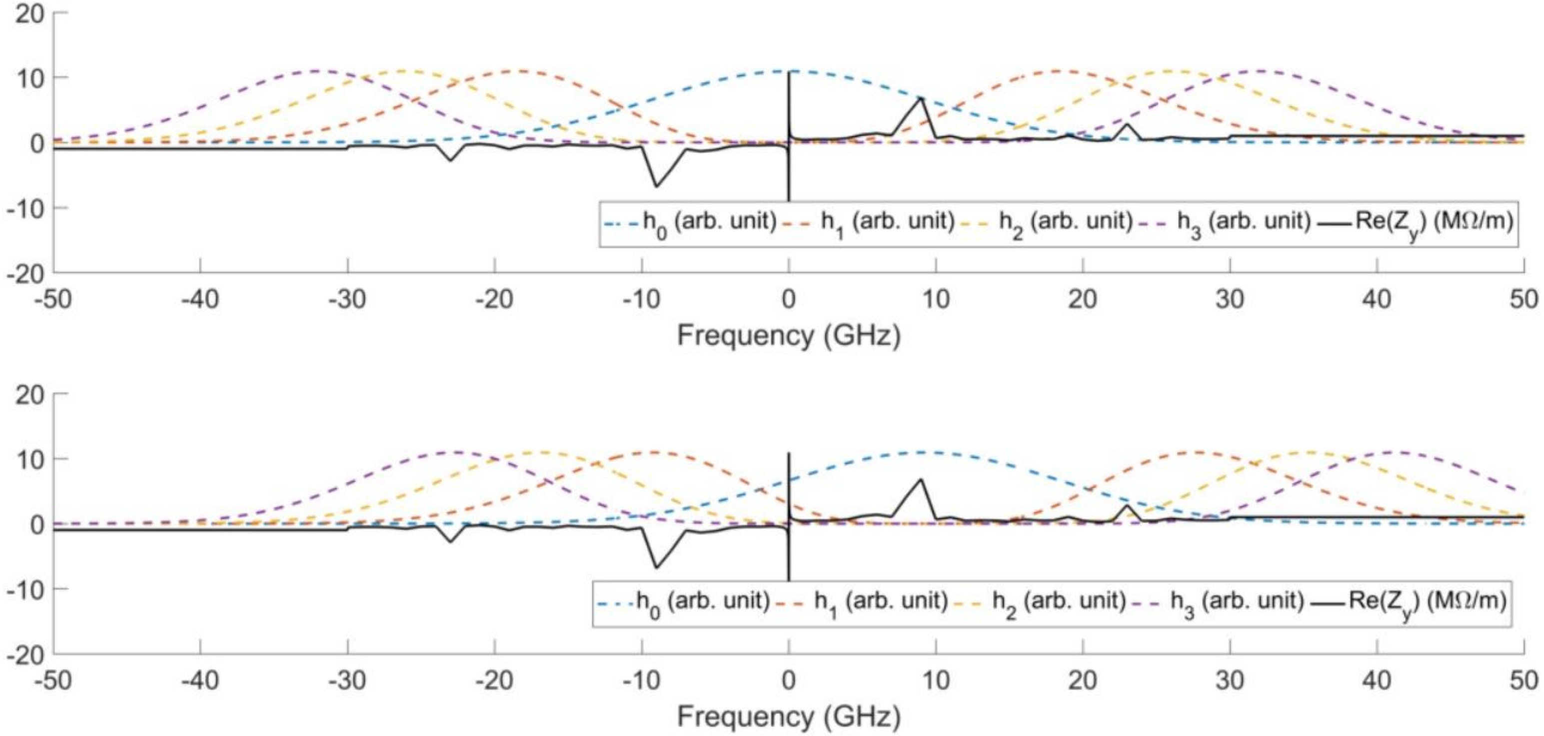
RW – Head-Tail Damping



As the real part of the transverse impedance at odd symmetry $Re[Z_\perp(-\omega)] = -Re[Z_\perp(\omega)]$, the negative frequencies in the equation will contribute to the instability while the positive frequencies provide damping.

When chromaticity is zero, the positive and negative frequency contributions cancel out for “broad band" impedances and only "narrowband" type impedances contribute to the instability.

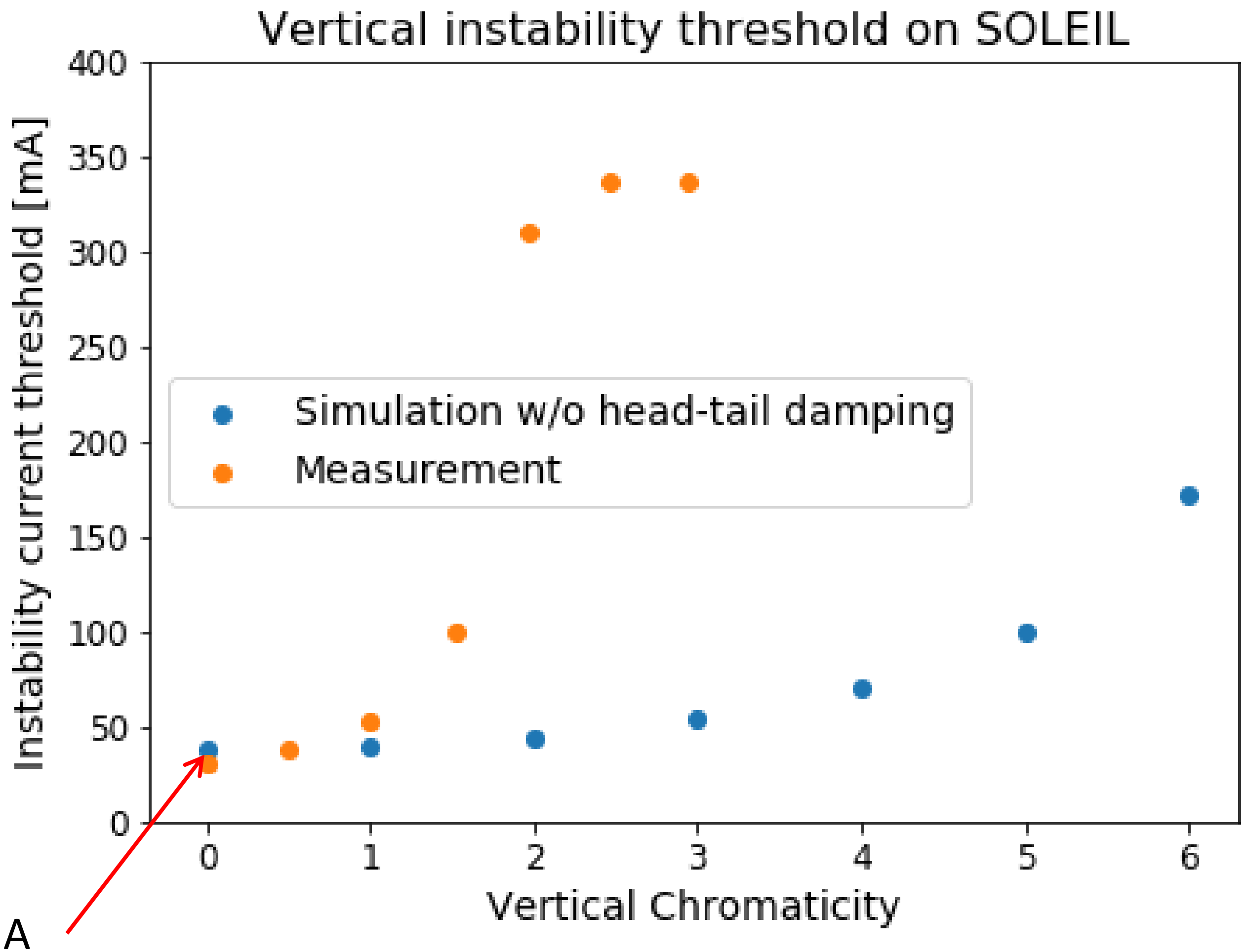
RW – Head-Tail Damping



When the chromaticity is non-zero, this cancellation is no longer effective because the frequency spectrum of the bunch h_m is displaced by ω_ξ.

By correcting the chromaticity to a positive value, we can use this displacement to damp the instability by using the stabilizing contribution of the positive frequencies of the “broadband” impedances (head-tail damping).

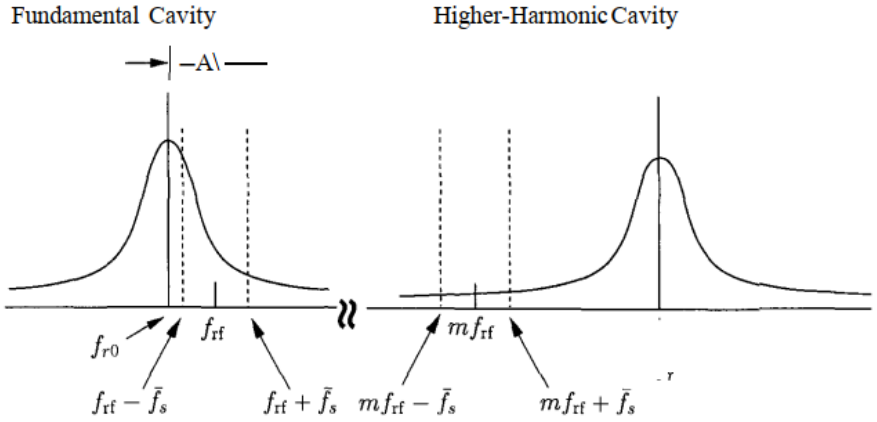
RW instability measurement on SOLEIL

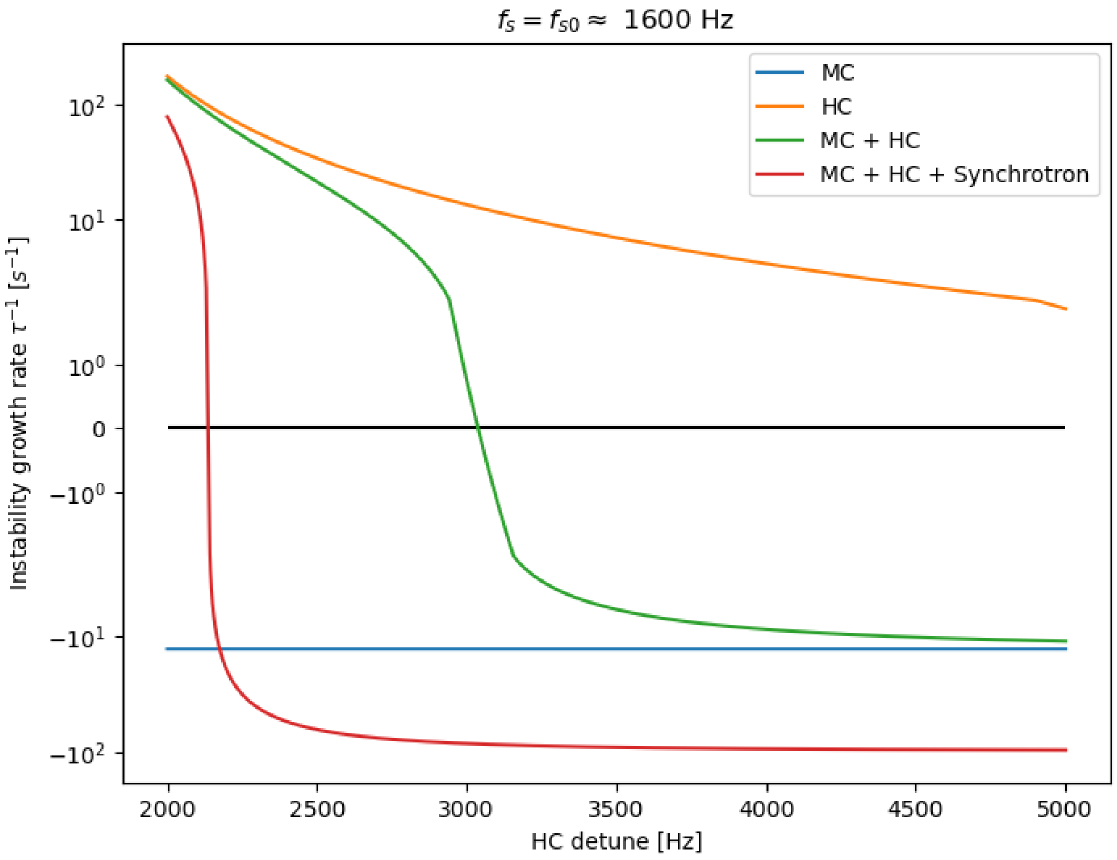


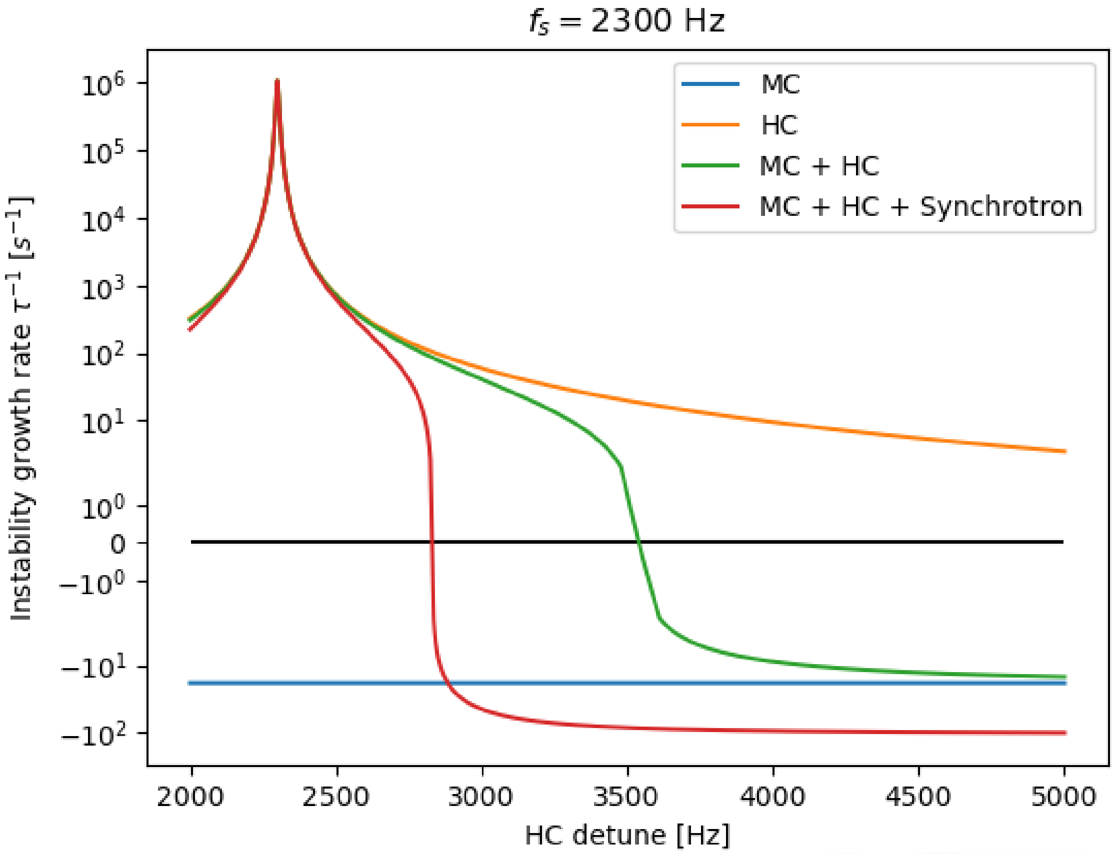
30 mA

Usual longitudinal coupled bunch formula applied to MC + HC impedance :

$$\frac{1}{\tau} = \mathcal{I}m\,\Omega \approx \frac{\eta e I_0 \omega_{\rm rf}}{2E_0T_0\bar{\omega}_s}\left\{\left[\mathcal{R}e\,Z_0^{\parallel}(\omega_{\rm rf}+\bar{\omega}_s) - \mathcal{R}e\,Z_0^{\parallel}(\omega_{\rm rf}-\bar{\omega}_s)\right] + m\left[\mathcal{R}e\,Z_0^{\parallel}(m\omega_{\rm rf}+\bar{\omega}_s) - \mathcal{R}e\,Z_0^{\parallel}(m\omega_{\rm rf}-\bar{\omega}_s)\right]\right\}$$







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:

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

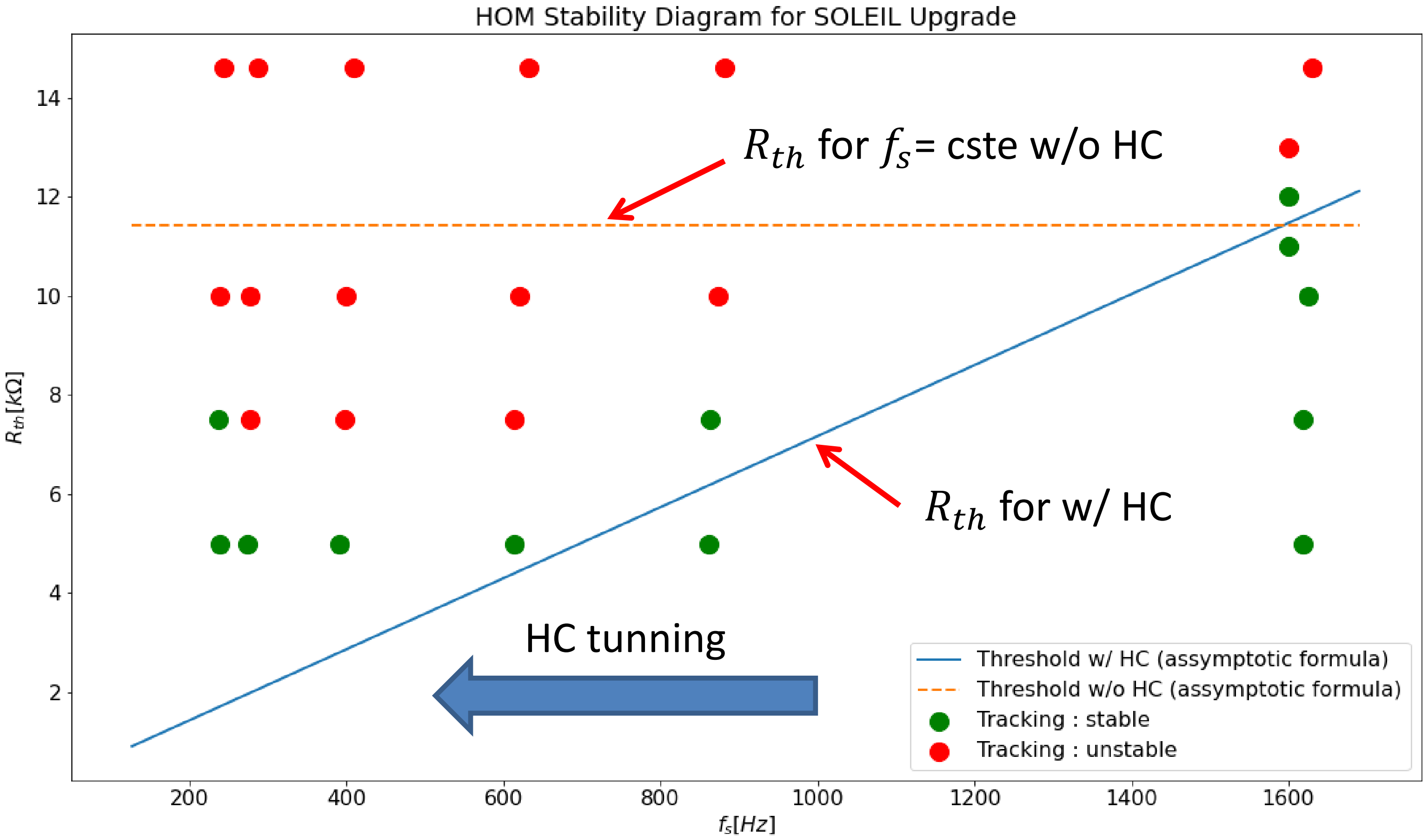
$$\omega_{\mu,n}^{\pm} = \left\{nM \pm (\mu + \nu_s)\right\}\omega_0$$

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 $\omega_{\mu,n} = \omega_r$, corresponding to the strongest instability growth rate:

$$\boxed{R_{th} = \frac{4\pi}{\tau_s \alpha_c}\frac{E}{I_0}\frac{f_s}{f_0}\frac{1}{\omega}}$$



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 lowering of the incoherent synchrotron frequency induced by the harmonic cavity lower the HOM threshold.
- In SOLEIL upgrade case, this effect is not compensated by the increased Landau damping due to the synchrotron frequency spread.