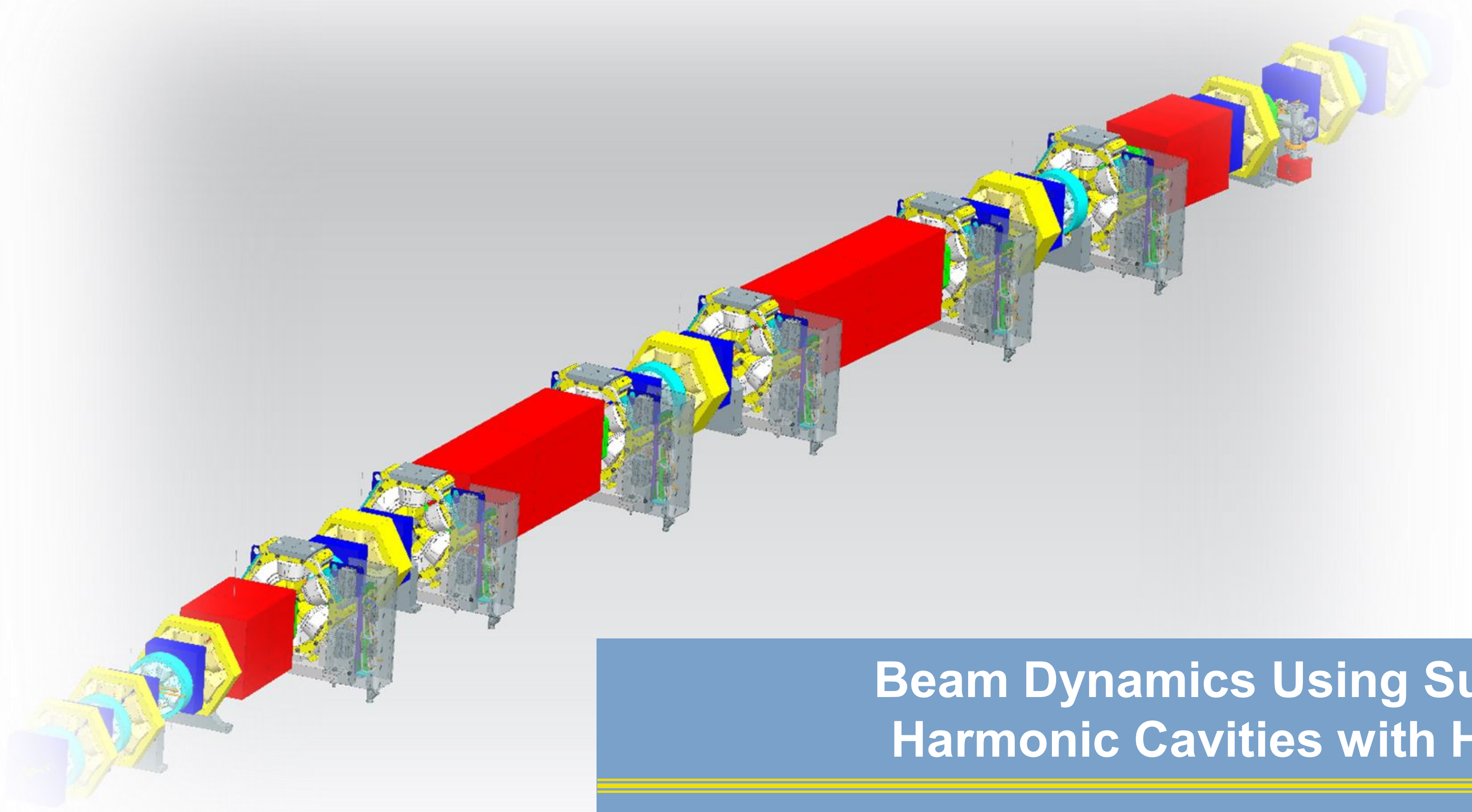
FLS 2023

Lucerne, 27th August - 1st September 2023



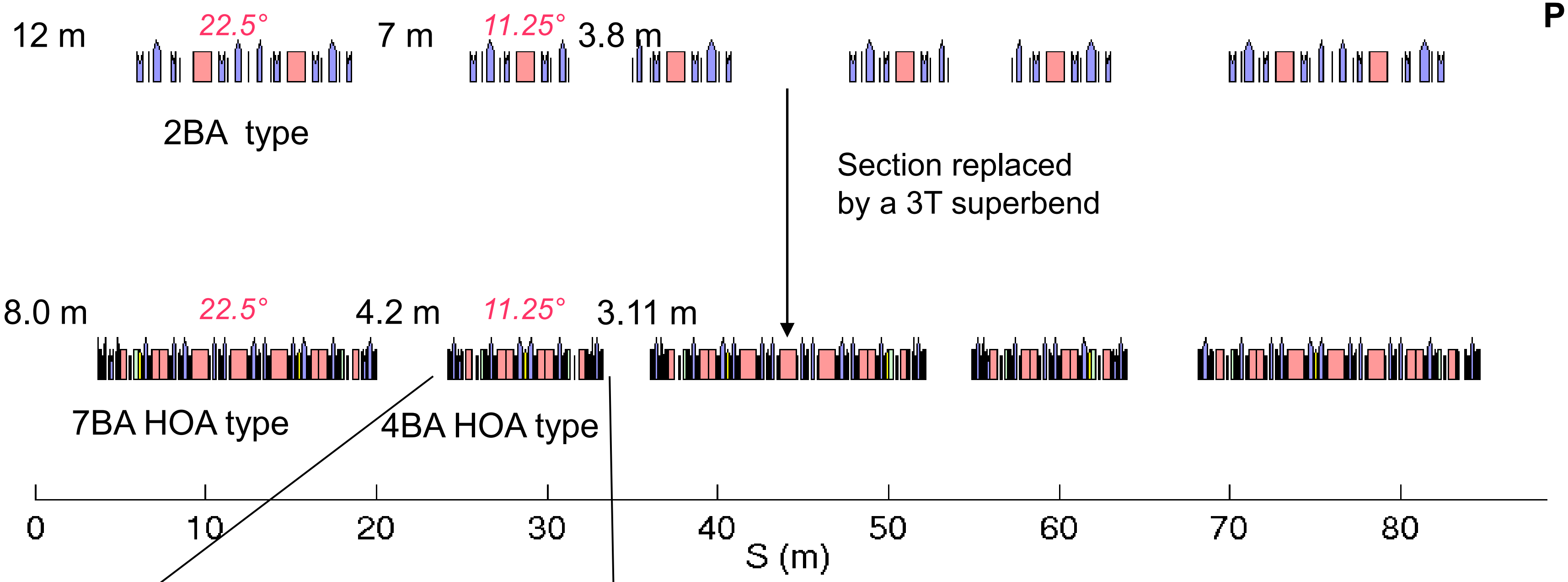
Beam Dynamics Using Superconducting Passive Harmonic Cavities with High Current per Bunch

Alexis Gamelin on behalf of SOLEIL II Project Team

Overview

1. Introduction
    1. SOLEIL II project
    2. Passive superconducting harmonic cavities
2. Beam dynamics simulations with harmonic cavities considering short range wakes
    1. PTBL instability
    2. Dipole-Quadrupole instability
    3. Coupling between cavity mode and dipole mode
3. Expected performances (emittance & lifetime) in high current per bunch modes

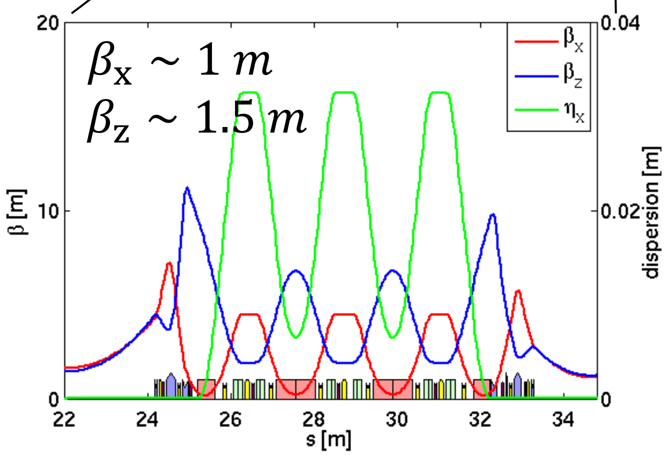
SOLEIL II TDR lattice



Section replaced by a 3T superbend

Present lattice at 4 nm.rad [32 dipoles]
46 % of straigth length

Upgrade at **84 pm.rad** [126 dipoles]
+reverse-bend to lower the emittance
25 % of straight length



Major features of the TDR lattice:

- Fit “at best” the beamlines positioning
- Permanent magnets for dipoles, quadrupoles and reverse bends
- Standard beam pipe inner diameter of 12 mm
- 95 % NEG coated ring
- Off axis injection (using MIK)
- Beam lifetime of ~ 3 hrs w/o HC

	Present	SOLEIL II
H-Emittance (2.75 GeV)	4 nm.rad	84 pm.rad
Circumference	354.10 m	353.97 m
Straight section number	24	20
Long straight length	12.00 m	8.00 / 9.00 m
Medium straight length	7.00 m	3.60 / 4.20 m
Short straight length	3.80 m	3.11 m
Straight length ratio	46 %	25 %
Betatron tunes H/V	18.16 / 10.23	54.2 / 18.3
Mom. comp. factor	$4.18\,10^{-4}$	$1.06\ 10^{-4}$
RMS energy spread	0.102 %	0.091 %
Energy loss per turn w/o IDs	917 keV	457 keV
Damping times s/x/z (ms)	3.3/3.3/6.6	7.9 /14.1 /12.2
RMS Nat. bunch length	15.2 ps	8.5 ps
RF main cavity Voltage	2.8 MV	1.8 MV

Harmonic cavities and timing modes

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

They are mainly used to lengthen the bunches which provide:

- Reduced intra-beam scattering (IBS)
- Increased Touschek lifetime

Harmonic cavities used in synchrotron light sources are quasi-exclusively passive, i.e. powered by the beam, so they mostly have been used in filling modes with high average current.

But it is in the “timing” modes where the current per bunch is high that both the IBS and Touschek effects are the strongest.

So, if we want to keep this type of operation modes in ultra-low emittance rings, the HCs should provide a large reduction of the IBS and Touschek effect.

Is it possible to have ultra-low emittance high current bunches ?

Current SOLEIL operation modes:

Operation mode	Total current	Current per bunch	Charge per bunch
Uniform	500 mA	1.2 mA	1.4 nC
Hybrid (3/4)	450 mA	1.44 mA	1.7 nC
8 bunch	100 mA	12.5 mA	14.8 nC
1 bunch	20 mA	20 mA	23.6 nC

Passive harmonic cavity

For a passive cavity at the m^{th} harmonic of the RF frequency f_{RF}, the only knob is the cavity tuning angle ψ or equivalently the cavity detuning Δf:

$$\Delta f = f_r - m f_{RF}$$

$$\tan(\psi) = Q\left(\frac{f_r}{m f_{RF}} - \frac{m f_{RF}}{f_r}\right) \approx 2Q\frac{\Delta f}{f_r}$$

Cavity quality factor

The voltage in such a passive cavity is given by:
(neglecting form factors)

Cavity shunt impedance

$$V_2 = 2 I_0 R_s cos(\psi) \approx I_0 \frac{R_s}{Q_0}\frac{m f_{RF}}{\Delta f}\sin(\psi)$$

Total beam current

To get long bunches, by flattening the total RF voltage, the voltage in the harmonic cavity needs to be able to reach:

$$V_2 = -\xi\frac{V_1 \sin(\phi_1)}{m \sin(\phi_2)} \approx \xi\frac{V_1}{m}$$

where

$$\xi = -\frac{m V_2 \sin(\phi_2)}{V_1 \sin(\phi_1)} =$$

- = 0 without HC
- = 1 at flat potential conditions

For a main RF voltage $V_1 = 1.8\ MV$ and a 4th harmonic cavity, to cover a range from 20 mA to 500 mA, it needs:

- ➢ $R_s \gg \frac{1.8 MV}{2*4*20\ mA} \approx 11.25\ M\Omega$ with a total R_s/Q_0 < 100 Ω for stability at high current (PTBL, …).
- ➢ Only possible with Super Conducting (SC) systems, typically $Q_0 \approx 10^8$, while Normal Conducting typically have $Q_0 \approx 10^4$.

RF System

RF system (for this presentation):

- Main NC RF : ESRF - EBS fundamental cavity
  - Rs (per cavity) = 5 $M\Omega$
  - Q_0 = 35 000
  - N_{cav} = 4
  - $\beta = 5$ (Q_L = 5 833)
  - V_c = 1.8 MV
  - $f_{RF} = 352\ MHz$
- Passive SC HC : Super3HC
  - m = 3 or m = 4
  - Rs (per cavity) = $4.5\ G\Omega$
  - $Q_0 = 10^8$
  - $R/Q = 45\ \Omega$
  - N_{cav} = 2

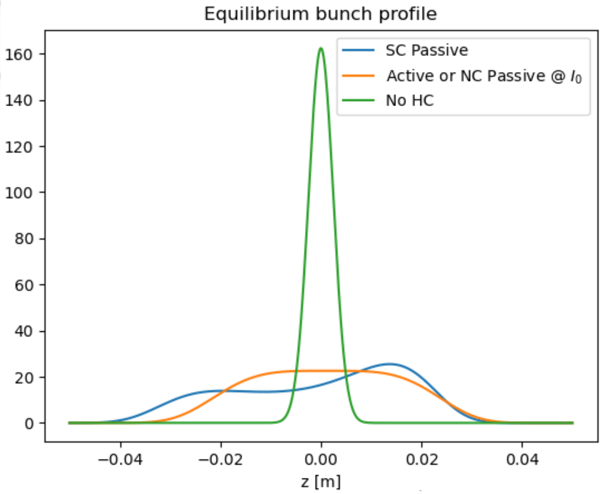
$$V_{tot}(t) = V_1\cos(\omega_{RF}t+\phi_1)+V_2\cos(m\omega_{RF}t+\phi_2)$$

Because it is SC, ψ is fixed to $\pi/2$ and ϕ_2 to $-\pi/2$, the conditions to lengthen the bunches are quite simple:

$$\cos(\phi_1)\approx\frac{U_{loss}}{eV_1} \qquad V_2\approx\xi\frac{V_1\sin(\phi_1)}{m}\approx I_0\frac{R}{Q}\frac{mf_{RF}}{\Delta f}$$

Which gives the (near) flat potential conditions for $\xi=1$:

$$\frac{dV_{tot}}{dt}(0)=\xi\omega_{RF}\sin(\phi_1)\left(1-\frac{1}{\xi}\right) \qquad \frac{d^2V_{tot}}{dt^2}(0)=-\frac{\omega_{RF}U_{loss}}{e}$$



For a SC passive HC:

- The MC phase ϕ_1 is the same as the one used without HC.
- The second derivative of the RF voltage can never be cancelled and is fixed by the losses.
- The MC and HC are totally independent systems.

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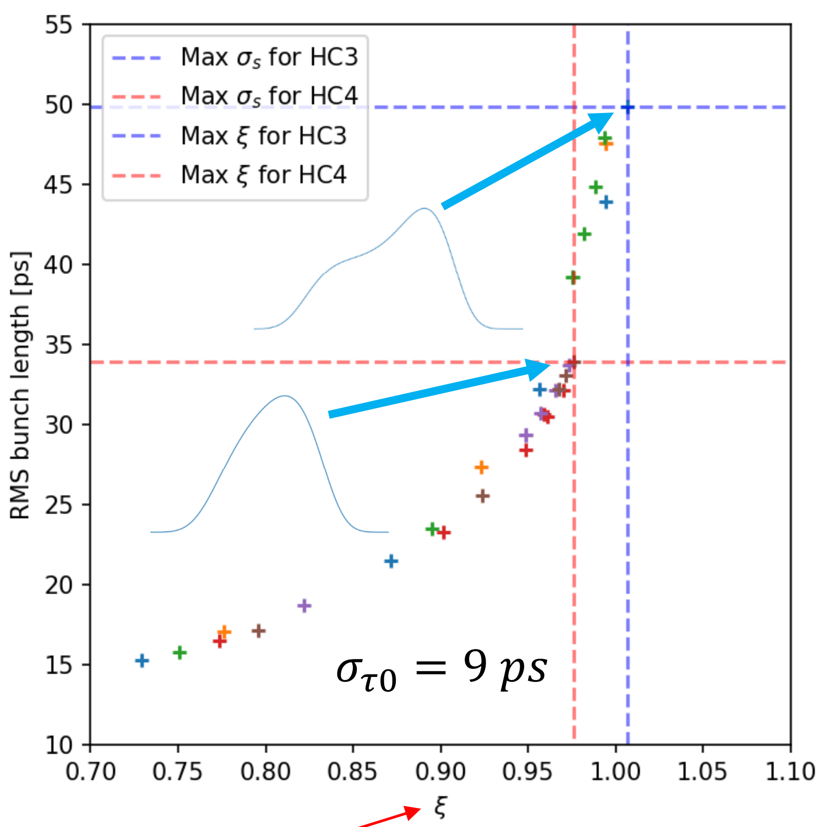
Uniform filling at 500 mA

Here are the stable settings found for a 3rd HC and a 4th HC for the SOLEIL II using multi-bunch tracking taking into account the beam loading in the main and harmonic cavity (mbtrack2[1]):



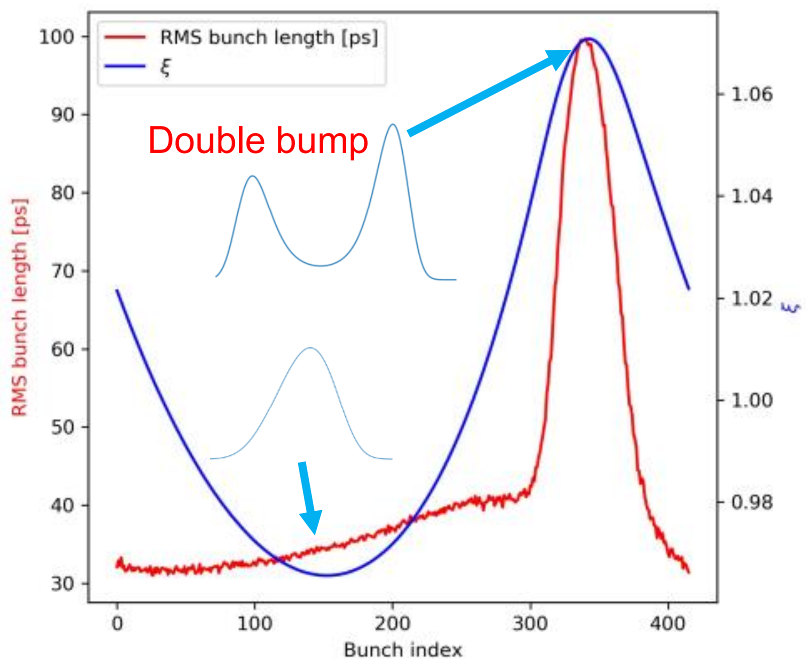
$\xi = -\frac{mV_2\sin(\phi_2)}{V_1\sin(\phi_1)}$ is the ratio of the harmonic "force" to the main cavity one

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

The limitation, in both cases, is the $l = 1$ instability [2] / PTBL[3] but it is happening at different distance from $\xi = 1$.

The PTBL threshold increases with the bunch length. It then explains why the 3rd HC threshold is higher than the 4th HC as it naturally produce longer bunches.

At a given turn during the instability



How bunch lengthening from additional impedances impacts these results ?

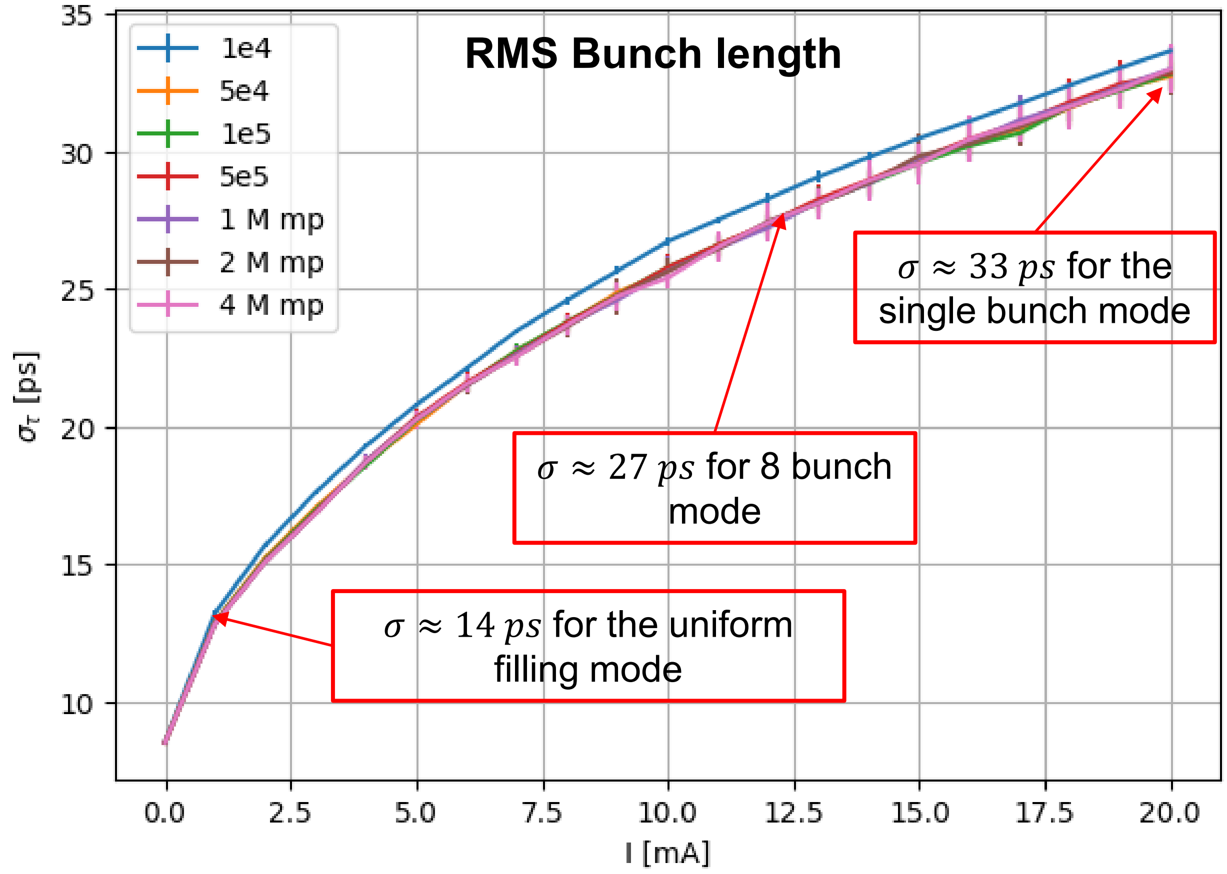
[1] Gamelin, A., Foosang, W., & Nagaoka, R. mbtrack2, a Collective Effect Library in Python. IPAC'21

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

[3] He, T., Li, W., Bai, Z., & Wang, L. (2022). Periodic transient beam loading effect with passive harmonic cavities in electron storage rings. *PRAB*, *25*(2), 024401.

Tracking vs single bunch current

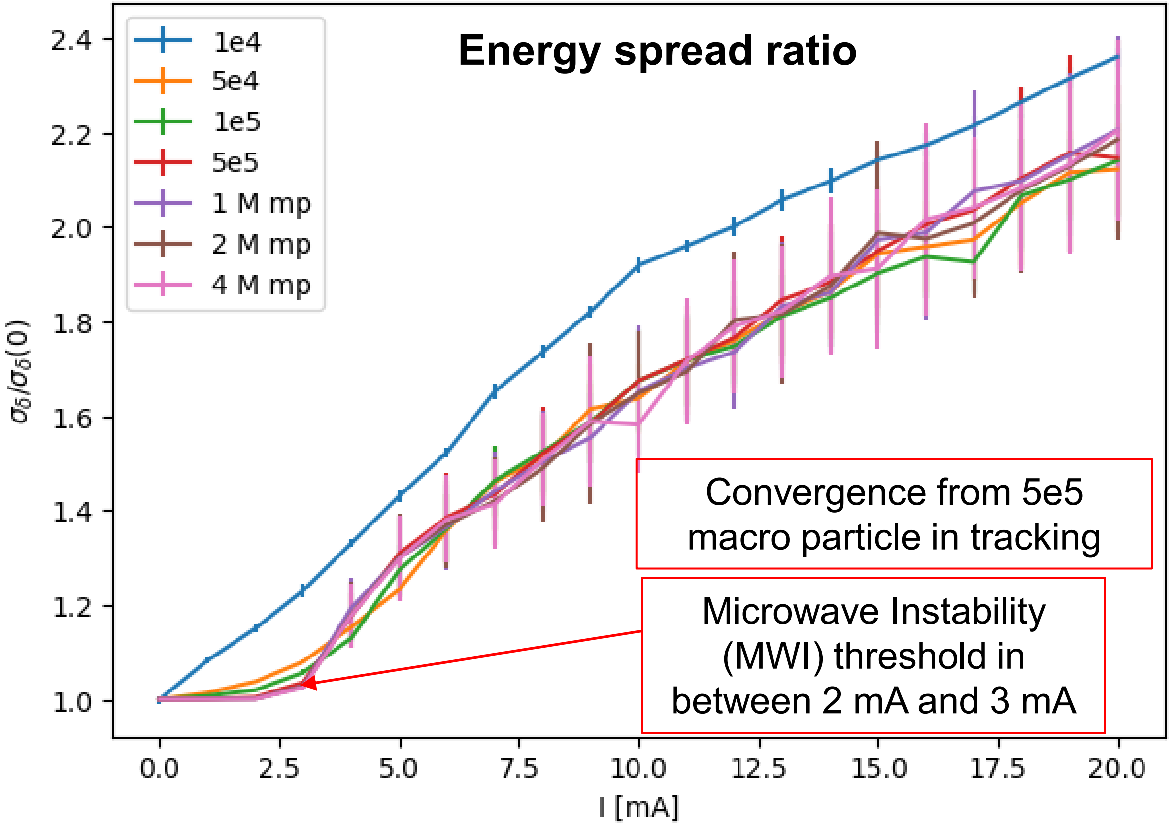
Single bunch collective effects:
- Considering a preliminary TDR impedance model (RW + geom. impedance, +20 components including NEG, tapers, IDs, …).
- Treated as wake function in the tracking (so no broad band fit).



$\sigma \approx 33\ ps$ for the single bunch mode

$\sigma \approx 27\ ps$ for 8 bunch mode

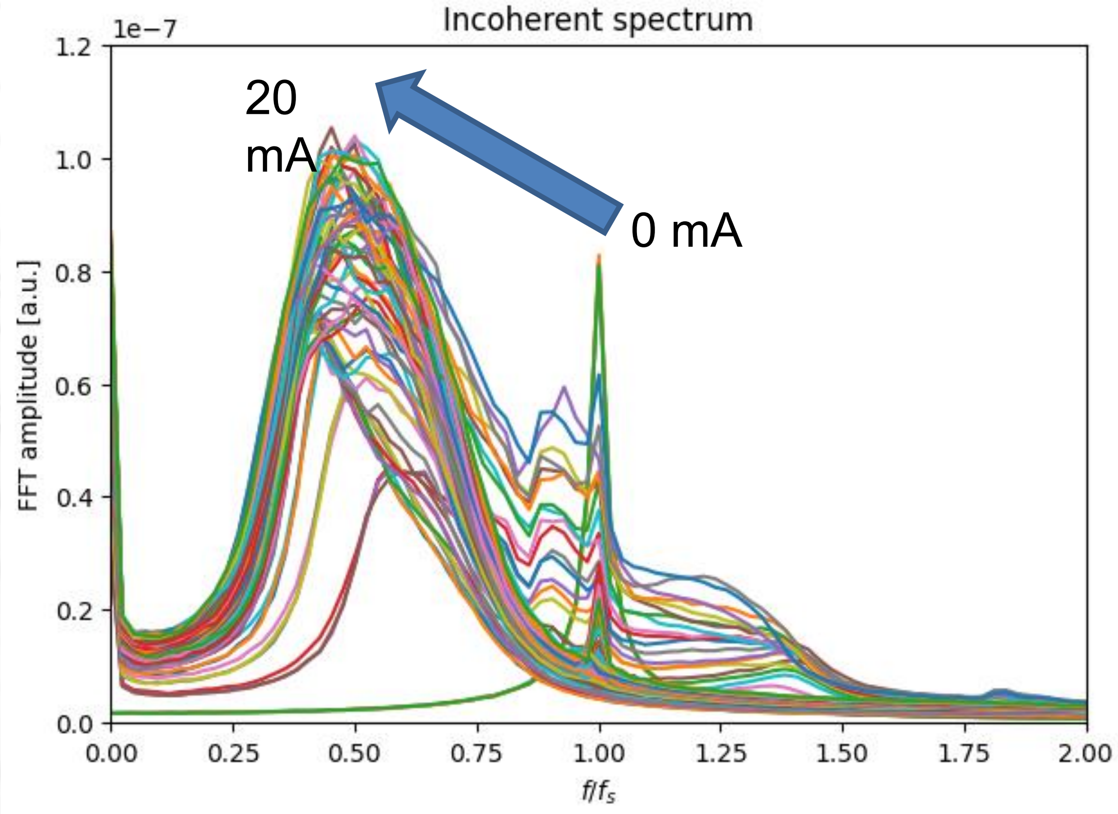
$\sigma \approx 14\ ps$ for the uniform filling mode



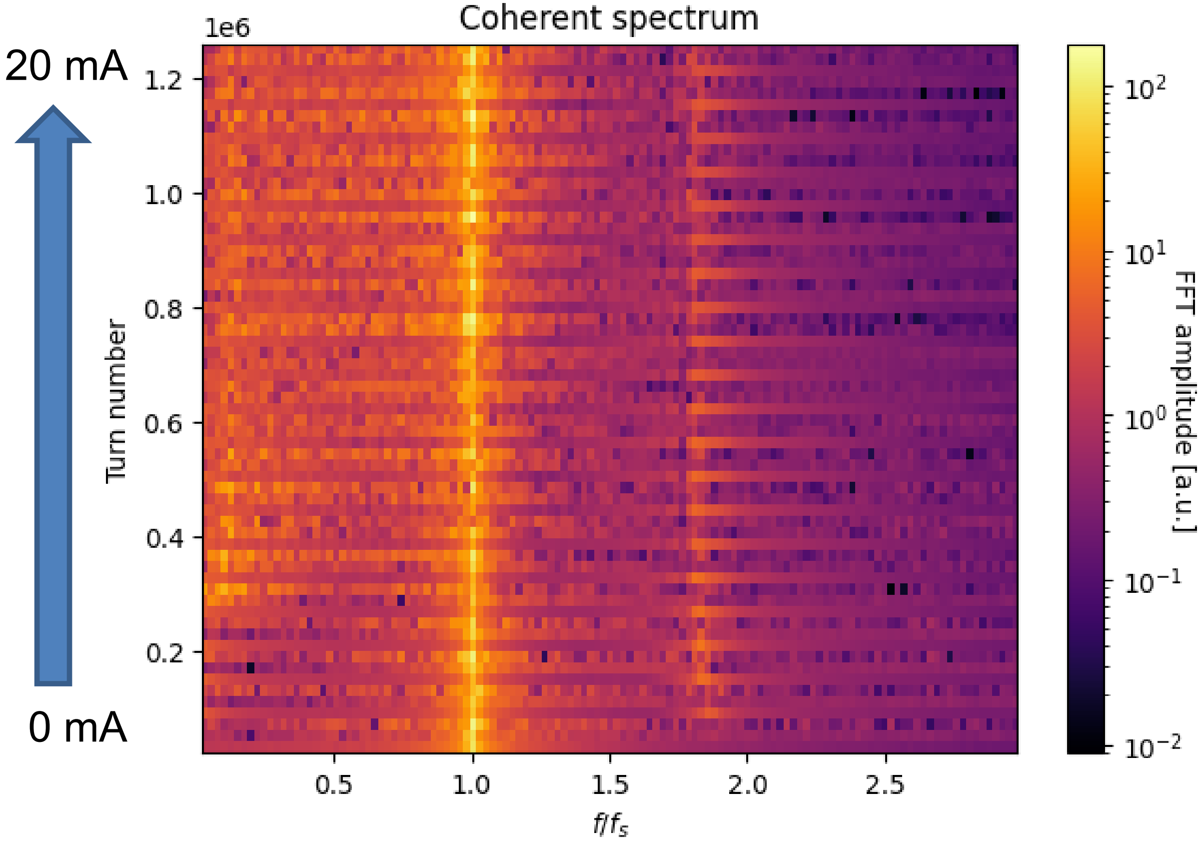
Convergence from 5e5 macro particle in tracking

Microwave Instability (MWI) threshold in between 2 mA and 3 mA

Tracking vs single bunch current



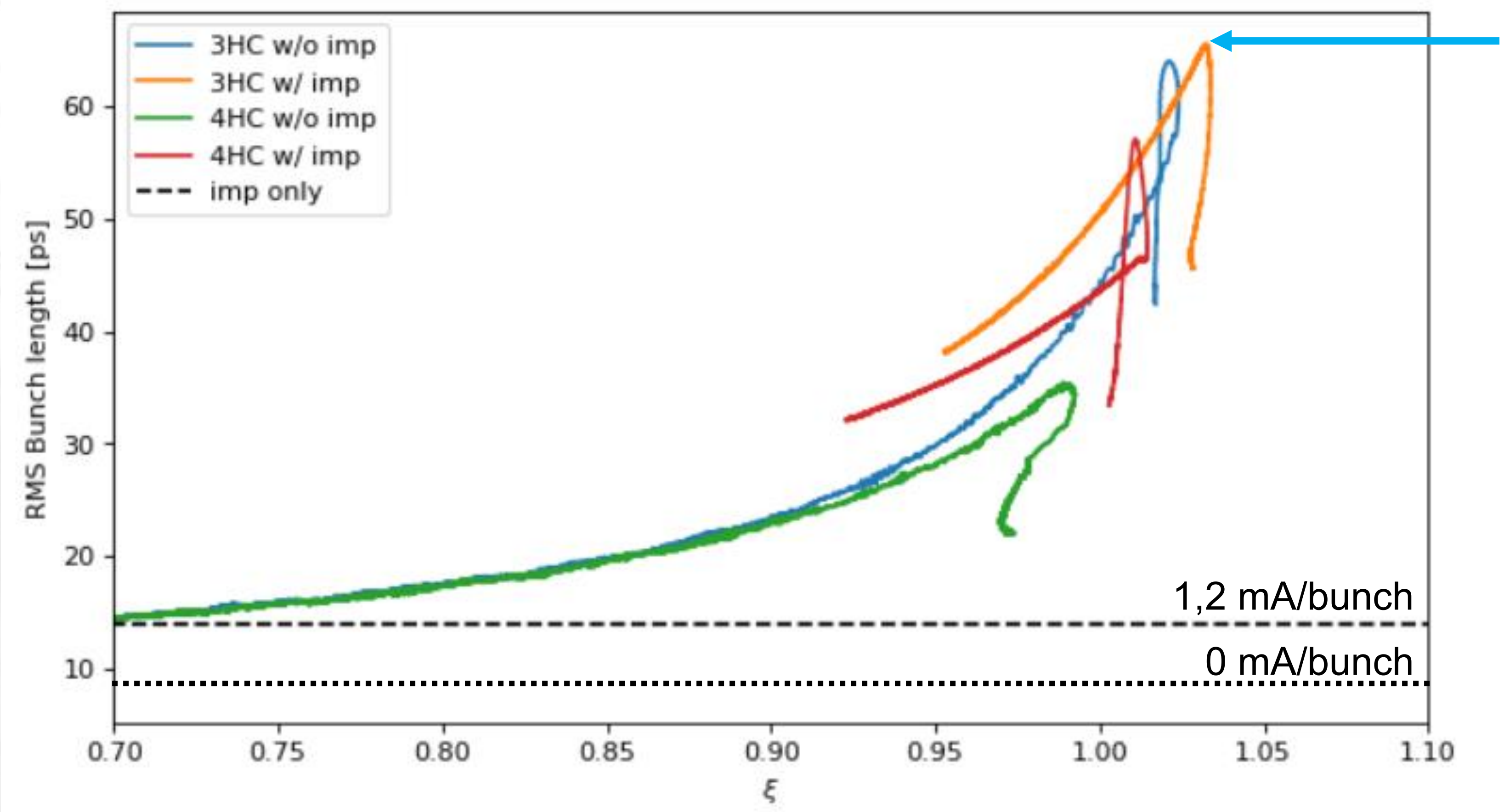
Go from a sharp peak at zero current to a spread out bump at higher current (MWI regime) at lower frequency (incoherent tune shift).



The synchrotron mode m=1 is constant because the (negative) incoherent tune shift is compensated by the dynamic coherent frequency shift for mode m=1 (Ng book p.68 & p.206)

The synchrotron mode m=2 (slightly shifted downward) is visible in the MWI regime.

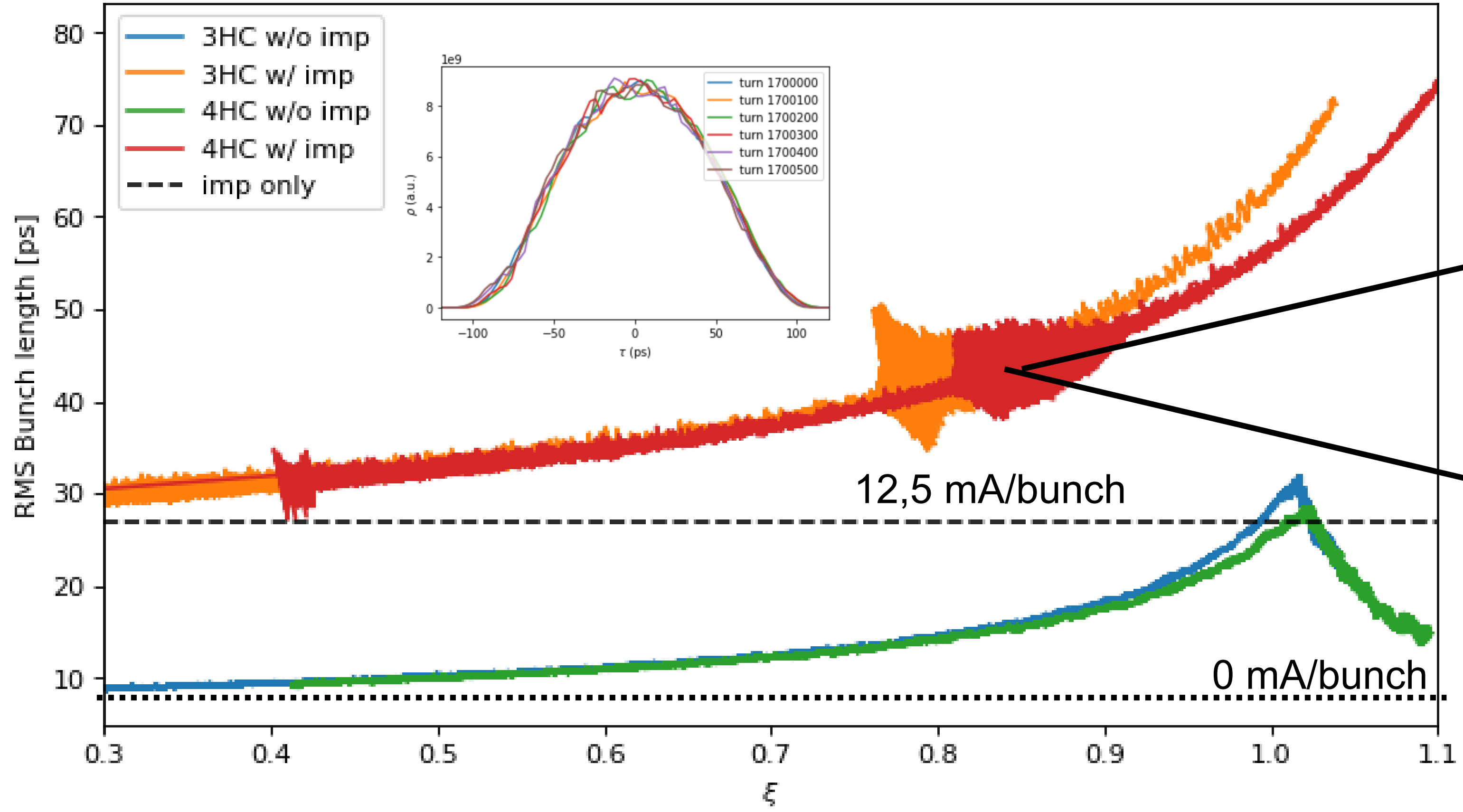
Uniform filling at 500 mA (with SB collective effects)



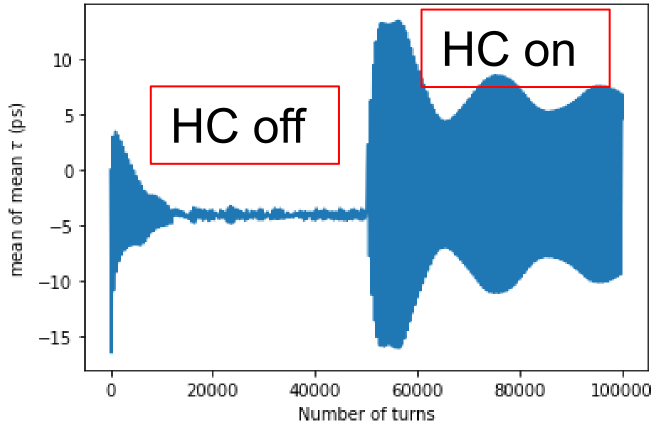
Harmonic cavity detuning decreases

- The turning points corresponds to the threshold of PTBL instability.
- The instability leads to a decrease of the average harmonic voltage and thus a decrease of the average ξ for lower HC detuning.
- The added bunch lengthening from the impedance push the threshold toward higher values.

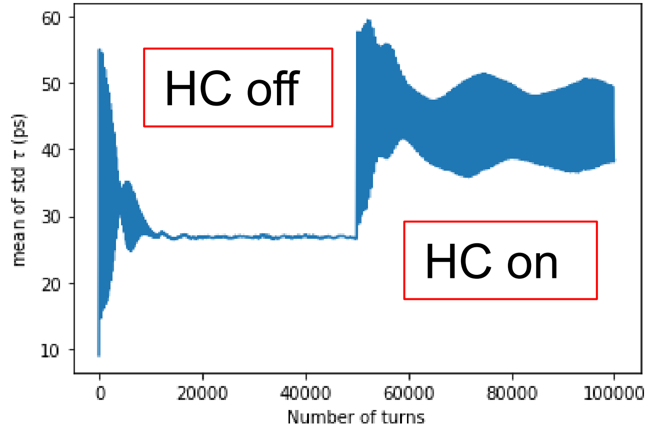
8 bunch mode at 100 mA (with SB collective effects)



Mean center of mass



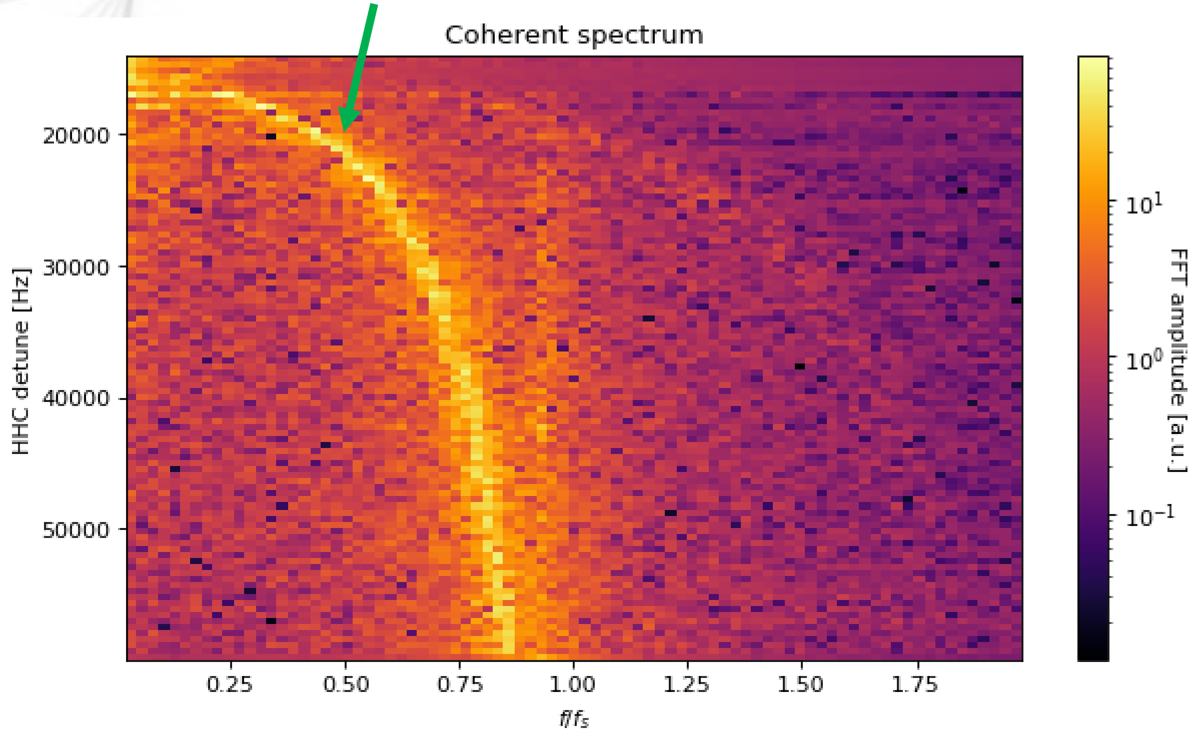
Mean RMS bunch length



- A dipole-quadrupole instability is observed in a given tuning range when the single bunch collective effects are considered (MWI regime).
- This instability is observed at lower ξ (and lower bunch length) for the 3HC.
- It seems like a “weak” instability: excited beam but not beam loss

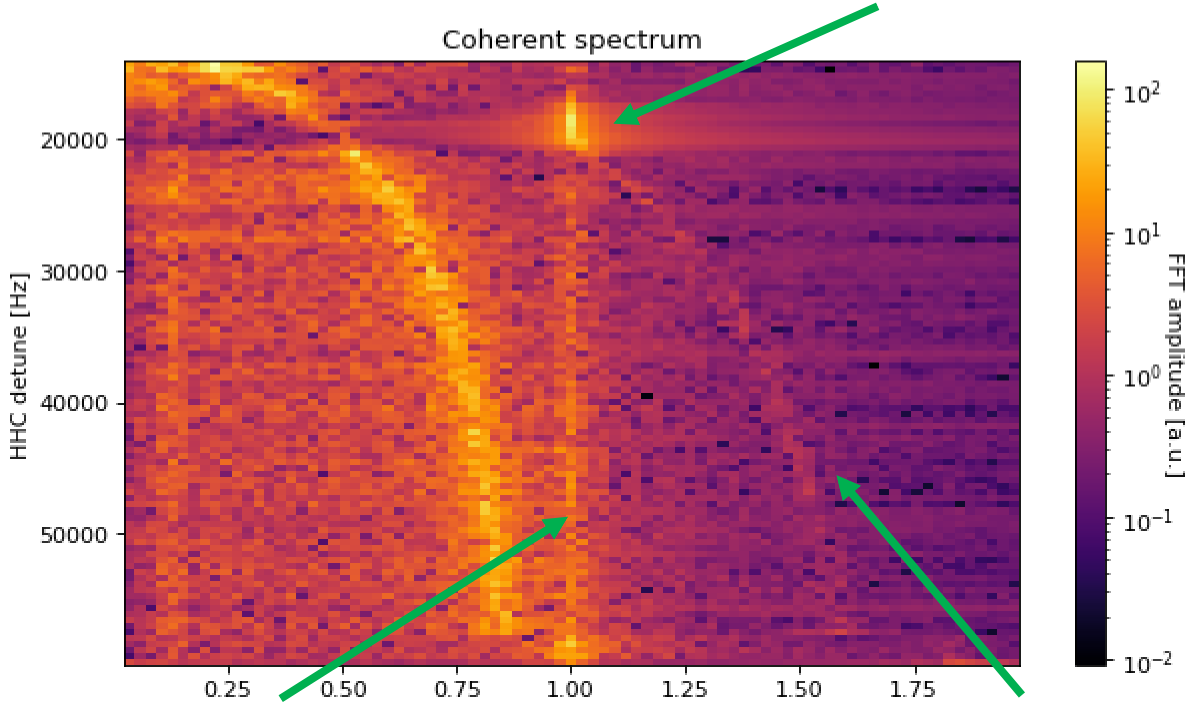
8 bunch mode at 100 mA (with SB collective effects)

Dipole (Robinson) mode: starts at f_{s_0} and then decreases when getting close to the (near) flat potential conditions.



3HC only

Dipole-Quadrupole instability



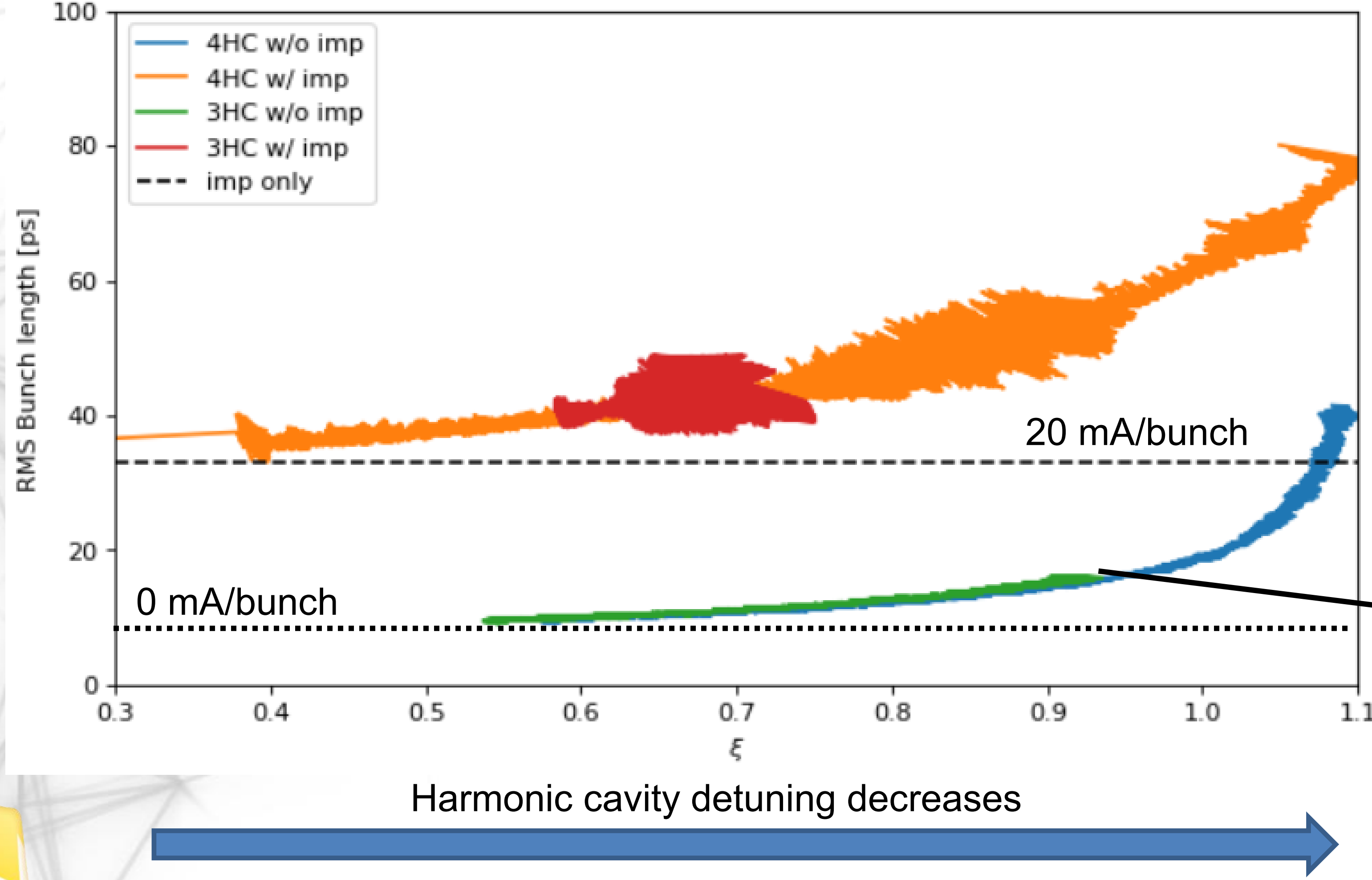
Dipole (synchrotron) mode

Quadrupole (Robinson) mode

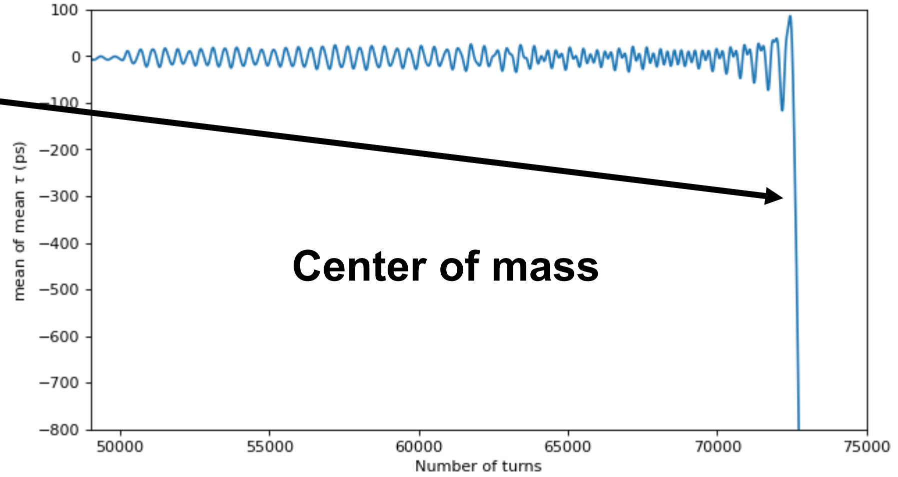
3HC + impedance model

Interaction between the dipole synchrotron mode excited in the MWI regime and the Robinson quadrupole mode.

1 bunch mode at 20 mA (with SB collective effects)

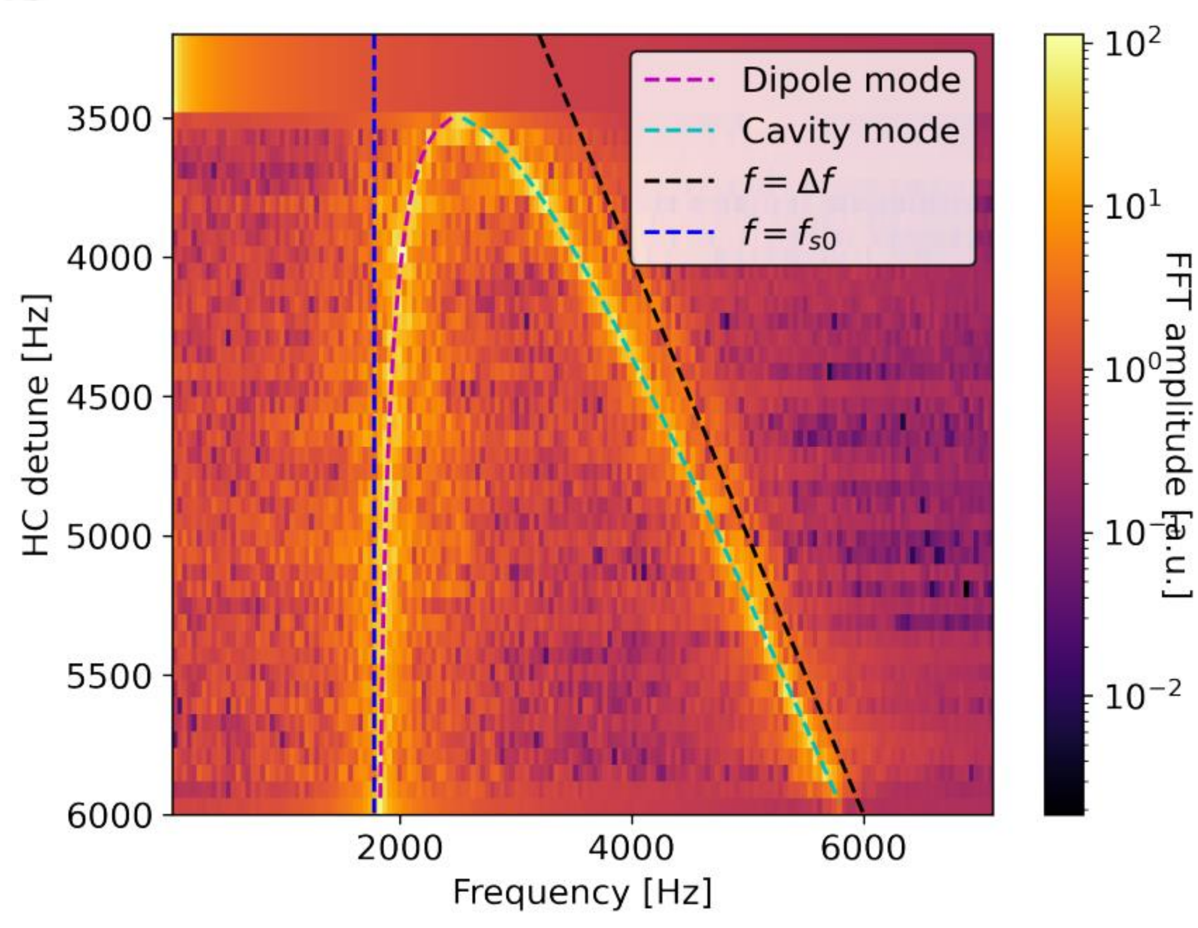


- The same kind of dipole-quadrupole oscillations as in 8 bunch mode is observed when impedance is added.
- In addition, fast beam losses are observed (w/ and w/o impedance).
- The fast beam loss happens sooner (in ξ and in detuning) when the impedance is taken into account.



Coupling between the cavity mode and dipole (Robinson) mode

The fast beam losses are driven by the mode coupling between the dipole (Robinson) mode originating from $f = f_{s0}$ and the cavity mode from $f = \Delta f$:



3HC only (no impedance model)

"The cavity mode can be understood as follows. When the bunch passes through the cavity, it excites, in addition to the equilibrium voltage with frequency f_{RF}, a transient voltage of frequency f_r […]. **When these two components of the voltage act back on the bunch, the revolution harmonics of the beam are modulated by $\Delta f = f_{RF} - f_r$. The modulated beam oscillation of frequency $f_{RF} \pm \Delta f$ then feeds back on the cavity leading to the cavity Robinson mode.**"

Towne, N., & Wang, J. M. (1998).
Spectrum of single bunch longitudinal dipole modes. *Physical Review E*, *57*(3), 3461.

The dipole (Robinson) and cavity modes are found numerically by solving the equation[1,2]:

$$\Omega^2 = \omega_s^2 + j\frac{eI_{av}\alpha_c}{E_0T_0} \times \sum_{p=-\infty}^{\infty}\left[p\omega_{rf}Z(p\omega_{rf}) - (p\omega_{rf}+\Omega)Z(p\omega_{rf}+\Omega)\right].$$

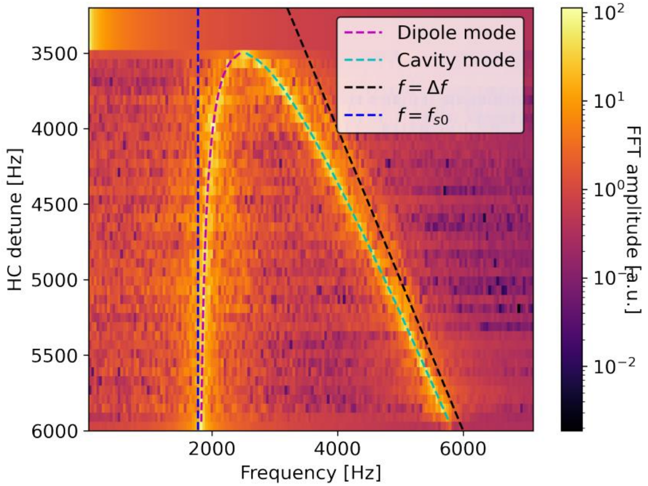
[1] Yamaguchi, T., Sakanaka, S., Yamamoto, N., Naito, D., & Takahashi, T. (2023). Systematic study on the static Robinson instability in an electron storage ring. *Physical Review Accelerators and Beams*, *26*(4), 044401.

[2] He, T., Li, W., Bai, Z., & Li, W. (2023). Mode-zero Robinson instability in the presence of passive superconducting harmonic cavities. *Physical Review Accelerators and Beams*, *26*(6), 064403.

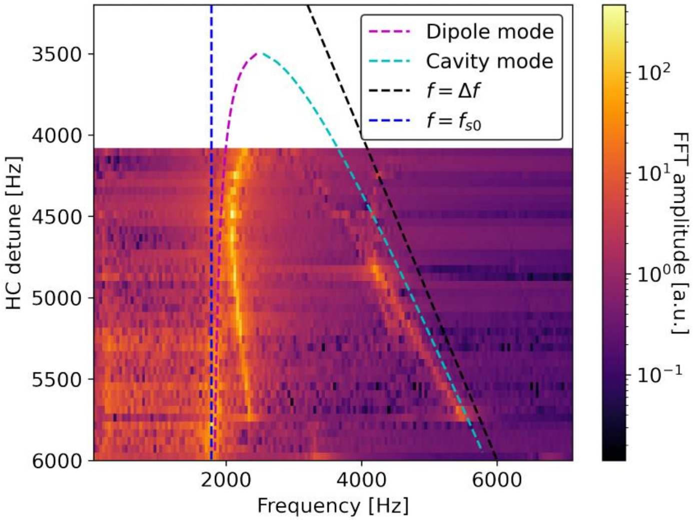
1 bunch mode at 20 mA (with SB collective effects)

- **The addition of the impedance model strengthens the coupling between the modes, which lowers the instability threshold.**
- Without SB collective effects, the 4th HC allows to lengthen the bunch all the way to double bump bunch in a stable way.
- For the 3rd harmonic, the bunch lengthening is very rapidly limited by the merging of these two modes.

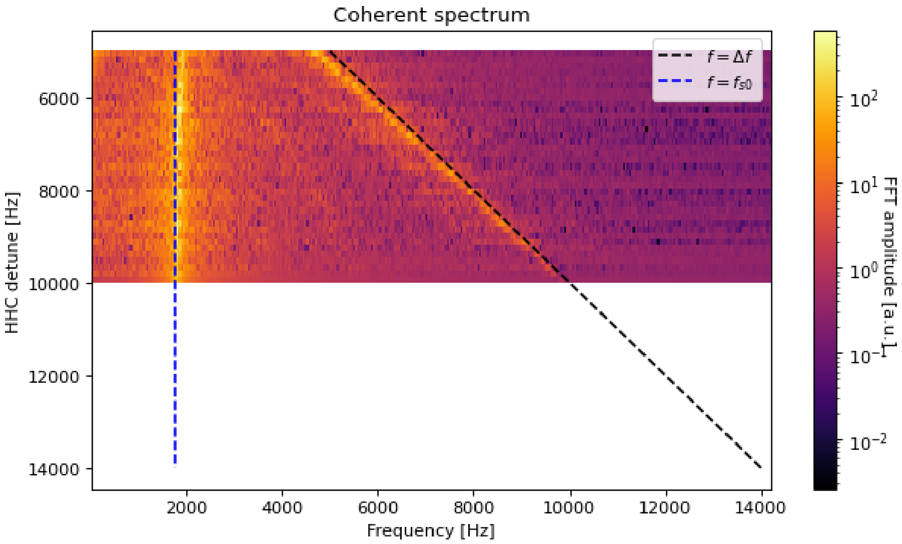
3HC only



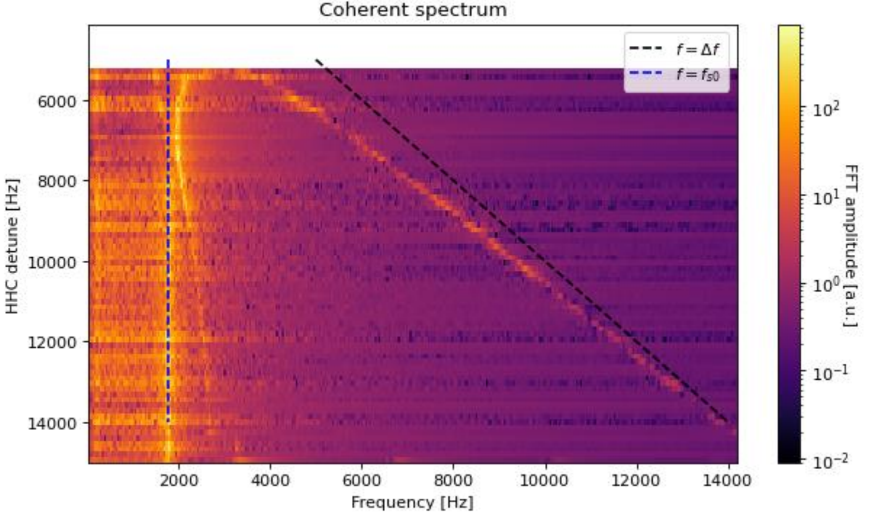
3HC + impedance model



4HC only



4HC + impedance model



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Workflow IBS + Touschek + HC + Impedance

Impedance model + HC

tracking
(mbtrack2)

Bunch length +
energy spread vs
bunch current

IBS computation
(analytic)

Bunch length +
energy spread
+ emittances

Piwinski
(pyAT)

Touschek
lifetime

To compute the lifetime for non-gaussian bunches :

ρ_0 is the longitudinal line density corresponding to the gaussian bunch of $\sigma = \sigma_{z0}$

$$\tau = \tau_{Piwinski} \times \frac{\int \rho_0^2(z)dz}{\int \rho^2(z)dz} = \tau_{Piwinski} \times R$$

Piwinski formula using the correct inputs but a fixed bunch length σ_{z_0}

ρ is an arbitrary longitudinal line density

Reference value for the uniform mode at 500 mA (for zero current bunch length):

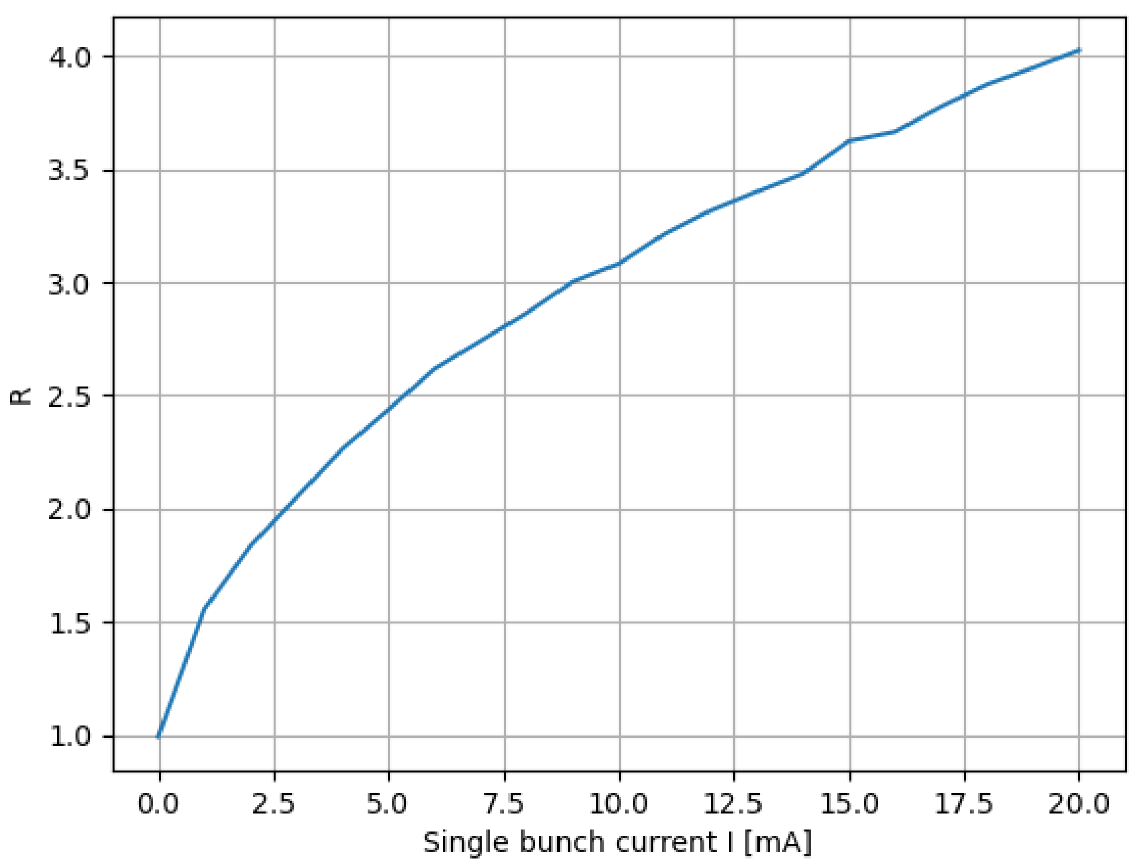
- σ_{z_0} = 8.6 ps (V_{RF}= 1.8 MV)
- σ_{δ_0} = 0.09 %
- ϵ_x = 84 pm.rad
- ϵ_y = 25 pm.rad
- I_{bunch} = 1.2 mA

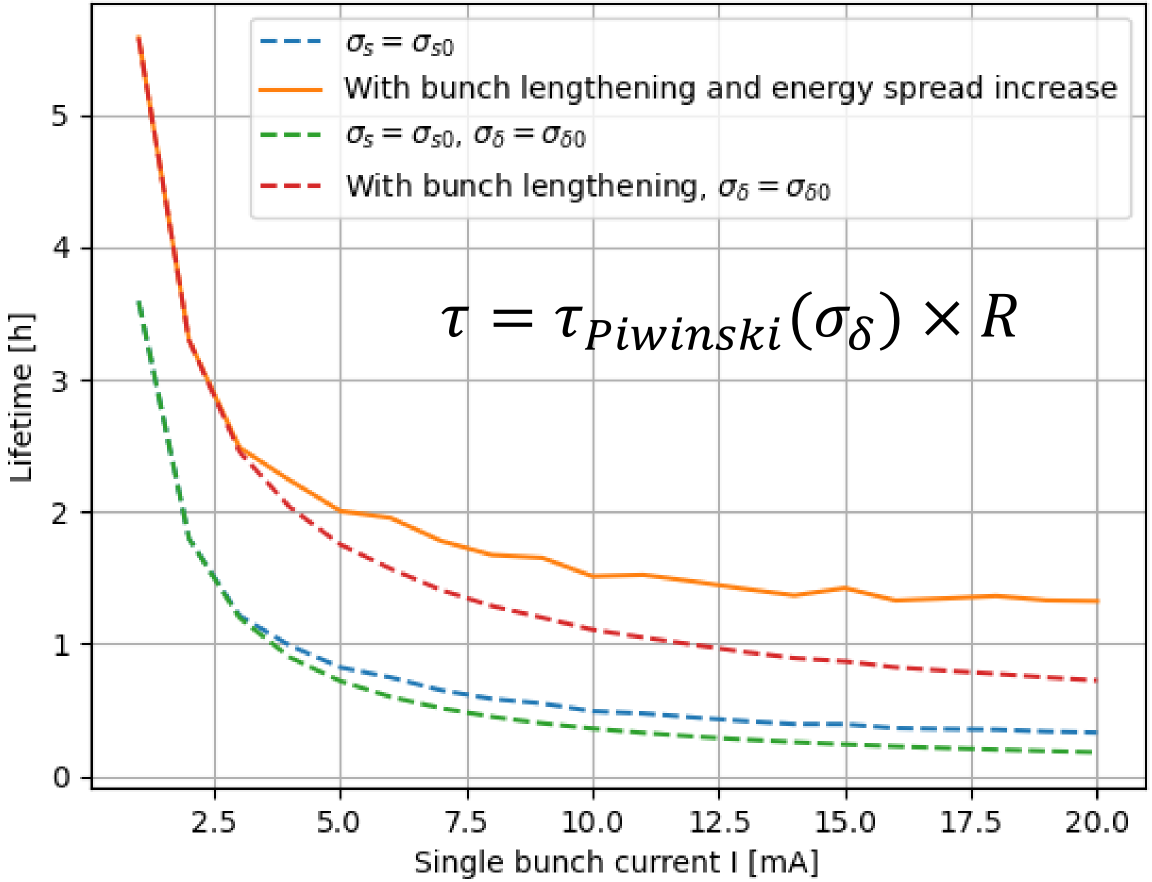
$\boxed{\tau = 3.0 \text{ h}}$

Bunch lengthening w/o HC

Bunch length and Touschek lifetime without harmonic cavity (and IBS neglected):

- The energy spread increase due to the Micro-Wave Instability (MWI) has a big impact on lifetime (+ 60% at 20 mA compared to $\sigma_\delta = \sigma_{\delta_0}$)



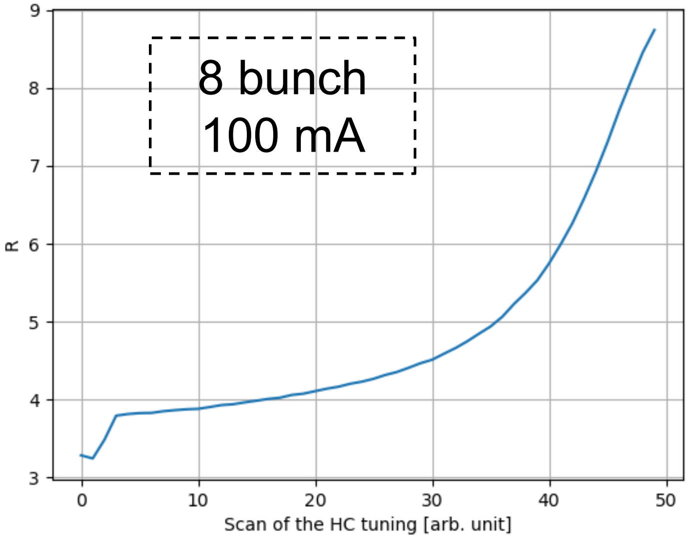


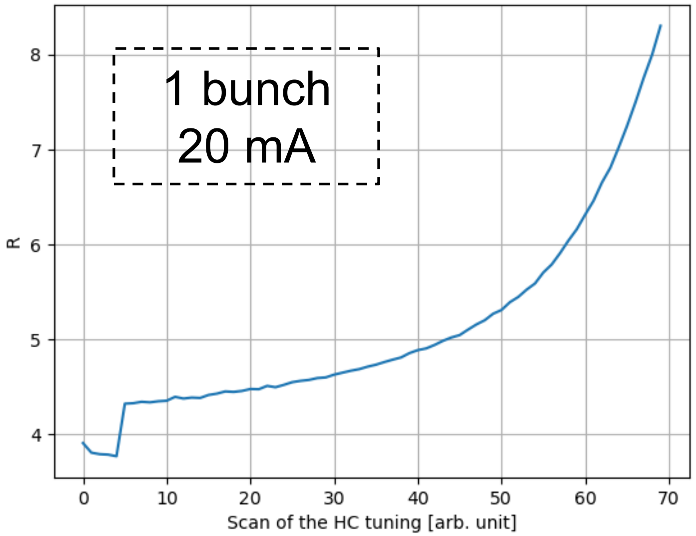
$$\tau = \tau_{Piwinski}(\sigma_\delta) \times R$$

IBS + Touschek

For a 4th SC HC (best performances at low current but not at 500 mA):

Operation mode	Harmonic cavity	Bunch length (RMS)	Current per bunch	Emittance H/V	Lifetime	Energy spread
Uniform	OFF	13 ps	1,2 mA	103/30 pm.rad	5.1 h	1.06E-3
Uniform	ON	46 ps	1,2 mA	91/27 pm.rad	17.0 h	0.97E-3
8 bunches	OFF	27 ps	12,5 mA	126/38 pm.rad	1.5 h	1.86E-3
8 bunches	ON	77 ps	12,5 mA	112/34 pm.rad	3.6 h	1.21E-3
1 bunch	OFF	33 ps	20 mA	130/39 pm.rad	1.3 h	2.31E-3
1 bunch	ON	69 ps	20 mA	122/36 pm.rad	2,5 h	1.55E-3





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1 bunch	ON	69 ps	20 mA	122/36 pm.rad	2,5 h	1.55E-3

- HC only provides marginal lifetime gain for high current per bunch modes because:
  1. The bunches are already quite long due to the impedance (R = 3.4 at 12.5 mA and R = 4 at 20 mA).
  2. HC bunch lengthening also reduces the energy spread and emittance blow-up.

- The vertical emittance is the only knob to increase further the lifetime but once past the round beam condition, the curve is mostly flat (due to the “frozen beam” Touschek effect).

Conclusions and perspectives

Lessons learned using HCs in high current per bunch modes

- Adding an impedance model to the HC tracking can considerably change the results (in particular for the high current per bunch regime).
- The PTBL instability threshold is increased for higher harmonic and more generally for longer bunches.
- Operation with HCs above the MWI threshold can lead to a dipole-quadrupole instability
- The coupling between the cavity mode (detuning) and dipole mode can limit the HC performances at low total current.
- The effectiveness of the HC bunch lengthening in reducing Touscheck/IBS effects is only the ratio R_{HC}/R_{noHC}

Other leads to achieve high current per bunch:

- Active NC HCs
  - Should be effective a low current
  - More complex than passive HCs
  - Beam stability is also an important issue
  - Very little experimental experience but developing fast (ESRF, ALBA/BESSY/DESY, …)
- Round beams
  - Reduce Touscheck/IBS effects
  - More complex lattice design & operation

After this study, some objectives are now changing for SOLEIL II project:

- Only two “major” operational modes:
  - Uniform filling at 500 mA (1,2 mA/bunch)
  - 32 bunches at 200 mA (6,25 mA/bunch)
  - Others (8 bunches and single bunch) kept as lower priority modes
- Now considering NC passive HC (ESRF-4th HC design) as baseline solution:
  - Similar performances at high current
  - Much cheaper than the SC passive option

Thank you for your attention!

Also … a post-doc positions is open at SOLEIL on beam dynamics:
https://www.synchrotron-soleil.fr/en/job-offers/post-doctoral-position-beam-dynamics

Contact: nagaoka@synchrotron-soleil.fr