# Harmonic cavity simulations using RF feedback for SOLEIL II

## HarmonLIP 2024

19/03/2024

Alexis Gamelin on behalf of SOLEIL II Project team

Part of this work has been performed within the frame of the WP2 collaboration among ESRF, HZB, KEK, PSI and SOLEIL

# Overview

- Previous option for SOLEIL II: SC passive HC
  - Previous target for RF system
  - Workflow with IBS + Touschek + HC + impedance
  - Results and lessons learned

- Present option for SOLEIL II: NC passive HC
  - New targets for RF system
  - Results without FBs
  - Proportional Integral loop
  - Direct RF FB
  - Results with FBs

### Objectives for the double RF system:

To provide suitable lifetime and IBS reduction, the RF system should be able to lengthen the bunches up to 100 ps FWHM (≈ 40 ps RMS) in all operation modes:

- Uniform filling @ 500 mA
- 8 bunches @ 100 mA
- 1 bunch @ 20 mA
- 16/32 bunches @ TBD

### Fixed parameters:

- Main RF : ESRF - EBS fundam[redacted]
  - Rs (per cavity) = 5 $M\Omega$
  - $Q_0$ = 35 000
  - $N_{cav}$ = 3 c[redacted]
  - $\beta$ [redacted]
  - $V_c$ [redacted]
  - $f_{RF}$ [redacted]

Shown at HarmonLIP 2022

### Options considered for the HC:

1. Passive SC : Super3HC (scal[redacted] 3 or m = 4)
   - Rs (per cavity) = 4,5 [redacted]
   - $Q_0$ = $10^8$
   - $R/Q$ [redacted]

[redacted] olution

[redacted] am Dynamics with a Superconducting [redacted] the SOLEIL Upgrade – IPAC'22

2. [redacted] SRF harmonic 2-cell cavity (m = 4)
   - [redacted] per cavity) = 2,4 $M\Omega$
   - $Q_0$ = 27 000
   - $R/Q = 88{,}8\ \Omega$
   - $N_{cav}$ = 2 or 3

**M. Diop talk on NC vs SC HCs**

**Paper: N. Yamamoto et al. - Feasibility study of an active harmonic cavity for bunch lengthening in an electron storage ring – PASJ'22**

3. Active NC : ESRF harmonic 2-cell cavity (m = 4)
   - Rs (per cavity) = 2,4 $M\Omega$
   - $Q_0$ = 27 000
   - $Q_L$ = 13 500 ($\beta = 1$)
   - $N_{cav}$ = 1 to 3

## Objectives for the double RF system:

To provide suitable lifetime and IBS reduction, the RF system should be able to lengthen the bunches up to 100 ps FWHM (≈ 40 ps RMS) in all operation modes:

- Uniform filling @ 500 mA
- 8 bunches @ 100 mA
- 1 bunch @ 20 mA
- 16/32 bunches @ TBD

## Fixed parameters:

- Main RF : ESRF - EBS fundamental cavity
  - Rs (per cavity) = 5 $M\Omega$
  - $Q_0$ = 35 000
  - $N_{cav}$ = 3 or 4
  - $\beta = 5$ ($Q_L$ = 5 833)
  - $V_c$ = 1,8 MV
  - $f_{RF} = 352\ MHz$

## Options considered for the HC:

1. Passive SC : Super3HC (scaled at m = 3 or m = 4)
   - Rs (per cavity) = $4{,}5\ G\Omega$
   - $Q_0 = 10^8$
   - $R/Q = 45\ \Omega$
   - $N_{cav}$ = 2

**This talk = baseline solution**

**Paper: A. Gamelin et al. - Beam Dynamics with a Superconducting Harmonic Cavity for the SOLEIL Upgrade – IPAC'22**

2. Passive NC : ESRF harmonic 2-cell cavity (m = 4)
   - Rs (per cavity) = 2,4 $M\Omega$
   - $Q_0$ = 27 000
   - $R/Q = 88{,}8\ \Omega$
   - $N_{cav}$ = 2 or 3

**M. Diop talk on NC vs SC HCs**

**Paper: N. Yamamoto et al. - Feasibility study of an active harmonic cavity for bunch lengthening in an electron storage ring – PASJ'22**

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   - $Q_0$ = 27 000
   - $Q_L$ = 13 500 ($\beta = 1$)
   - $N_{cav}$ = 1 to 3

# Workflow IBS + Touschek + HC + Impedance

impedance model + HC → tracking (mbtrack2) → Bunch length + energy spread vs bunch current → IBS computation (analytic via elegant) → Bunch length + energy spread + emittances → Touschek lifetime

Piwinski (pyAT)

Lattice → Touschek lifetime

**To compute the lifetime for non-gaussian bunches :**

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

$\rho_0$ is the longitudinal line density corresponding to the gaussian bunch of $\sigma = \sigma_{z0}$

Piwinski formula using the correct inputs but a fixed bunch length $\sigma_{z_0}$

$\rho$ is an arbitrary longitudinal line density

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

- $\sigma_{z_0} = 8.6$ ps ($V_{RF}$= 1.8 MV)
- $\sigma_{\delta_0} = 0.09$ %
- $\epsilon_x$ = 84 pm.rad
- $\epsilon_y$ = 25 pm.rad
- $I_{bunch} = 1.2$ mA

**$\tau$ = 3.0 h**

# Performances using SC passive HC

- Using this method, we evaluated the performances that we could reach in the different operation modes with maximum bunch lengthening

- Lifetime in single bunch and 8 bunch mode is quite close to the **minimum of 2h set by radioprotection** at SOLEIL

- But users are asking for FWHM bunch length < 100 ps in timing modes!

Table 2: Performance in different operation modes with and without SC HC (RMS values for $\sigma_z$ and $\sigma_\delta$).

| Operation Mode | HC | Bunch Length | Current per Bunch | Emittance H/V | R | Lifetime | Energy Spread |
|---|---|---|---|---|---|---|---|
| Uniform | Off | 13 ps | 1.2 mA | 103/30 pm.rad | 1.6 | 5.1 h | $1.06 \times 10^{-3}$ |
| Uniform | 3HC | 64 ps | 1.2 mA | 90/27 pm.rad | 7 | 22.4 h | $0.95 \times 10^{-3}$ |
| Uniform | 4HC | 46 ps | 1.2 mA | 91/27 pm.rad | 5 | 17.0 h | $0.97 \times 10^{-3}$ |
| 8 bunches | Off | 27 ps | 12.5 mA | 126/38 pm.rad | 3.4 | 1.5 h | $1.86 \times 10^{-3}$ |
| 8 bunches | 3/4HC | 77 ps | 12.5 mA | 112/34 pm.rad | 8.7 | 3.6 h | $1.21 \times 10^{-3}$ |
| 1 bunch | Off | 33 ps | 20 mA | 130/39 pm.rad | 4 | 1.3 h | $2.31 \times 10^{-3}$ |
| 1 bunch | 3HC | 41 ps | 20 mA | 132/40 pm.rad | 5 | 1.7 h | $1.88 \times 10^{-3}$ |
| 1 bunch | 4HC | 69 ps | 20 mA | 122/36 pm.rad | 8.3 | 2.5 h | $1.55 \times 10^{-3}$ |

| Operation mode | Harmonic cavity | Bunch length (FWHM) | Emittance H/V | Lifetime | Energy spread |
|---|---|---|---|---|---|
| 8 bunches | OFF | 81 ps | 126/38 pm.rad | 1.5 h | 1.86E-3 |
| 8 bunches | ON | 100 ps | 122/37 pm.rad | 1.7 h | 1.65E-3 |
| 1 bunch | OFF | 96 ps | 130/39 pm.rad | 1.3 h | 2.31E-3 |
| 1 bunch | ON | 100 ps | 131/39 pm.rad | 1.3 h | 2.01E-3 |

- HC only provides marginal gain lifetime for high current per bunch modes because:
  - The bunches are already quite long due to the impedance
  - HC bunch lengthening also reduces the energy spread (IBS & MWI) and emittance (IBS & SC) blow-up

For details, see: Gamelin, A., Gubaidulin, V., Loulergue, A., Marchand, P., Nadolski, L. S., Nagaoka, R., & Yamamoto, N. (2023). Beam dynamics using superconducting passive harmonic cavities with high current per bunch. *Proc. FLS'23*.

# Overview

- Previous option for SOLEIL II: SC passive HC
  - Previous target for RF system
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  - Results without FBs
  - Proportional Integral loop
  - Direct RF FB
  - Results with FBs

# Update of the operation modes

## New objectives for the double RF system:

To provide suitable lifetime, the RF system should be able to provide bunches as long as possible in the following operational modes:

- Uniform filling @ 500 mA
- 32 bunches @ 200 mA

The fact that 8 bunch mode (100 mA) has been replaced by the 32 bunch mode (200 mA) and that the single bunch mode will not be used with the HC now allows us to consider again the **option of a NC passive harmonic cavity** working in the 200 mA to 500 mA range.

| Operation mode | Machine | Total current | Current per bunch | Charge per bunch |
|---|---|---|---|---|
| Uniform | SOLEIL / SOLEIL II | 500 mA | 1.2 mA | 1.4 nC |
| Hybrid (¾) | SOLEIL | 450 mA | 1.44 mA | 1.7 nC |
| 8 bunch | SOLEIL / ~~SOLEIL II~~ | 100 mA | 12.5 mA | 14.8 nC |
| 1 bunch | SOLEIL / SOLEIL II (w/o HC) | 20 mA | 20 mA | 23.6 nC |
| 32 bunch | SOLEIL II | 200 mA | 6.25 mA | 7.4 nC |

## Option investigated in the following of this talk:

- **NC main RF cavity: ESRF-EBS fundamental cavity**
  - V = 1.7 MV
  - Rs = 5 MΩ
  - Q0 = 35 700
  - R/Q = 140 Ω
  - QL = 6000
  - Beta = 4.95
  - Ncav = 3 or 4

- **NC passive harmonic cavity: ESRF 4th HC 2-cell design**
  - m = 4
  - Rs = 2.358 MΩ
  - Q0 = 36 000
  - R/Q = 65.5 Ω
  - Beta = 0
  - Ncav = 1

# Set-up for tracking simulations

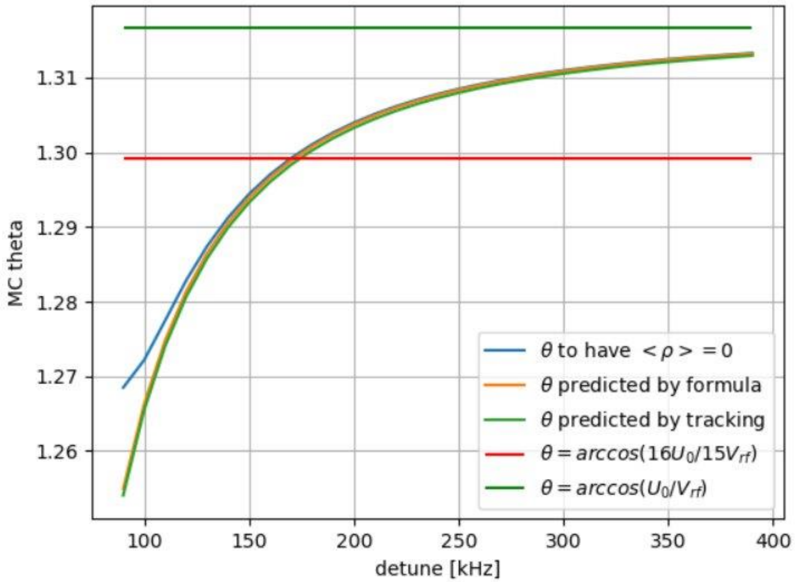
Simulation done with mbtrack2 (v0.5.0)

- With a NC passive HC, the MC settings depends on the HC tuning:

$$\phi_s = \arccos(\frac{U_0 + \Delta}{eV_{RF}})$$

$$\Delta = -eV_2\cos(\phi_2) = 2eI_0R_sF\cos(\psi)\cos(\Phi - \psi)$$

$$\Delta = eI_bk_{loss}T_0$$




- Momuntum compaction factor up to 3rd order:

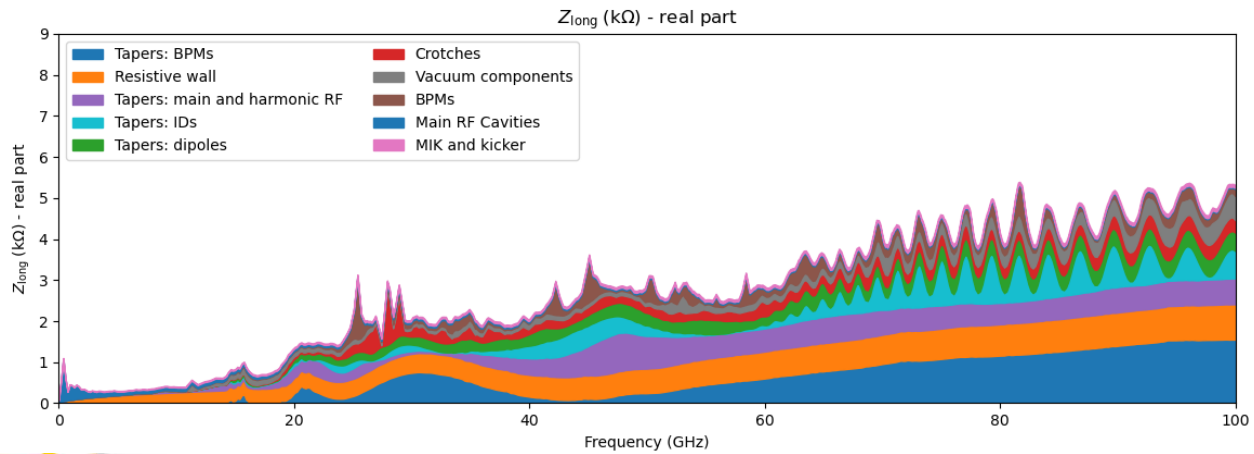
$$\alpha(\delta) = \alpha_c + \alpha_2\delta + \alpha_3\delta^2$$

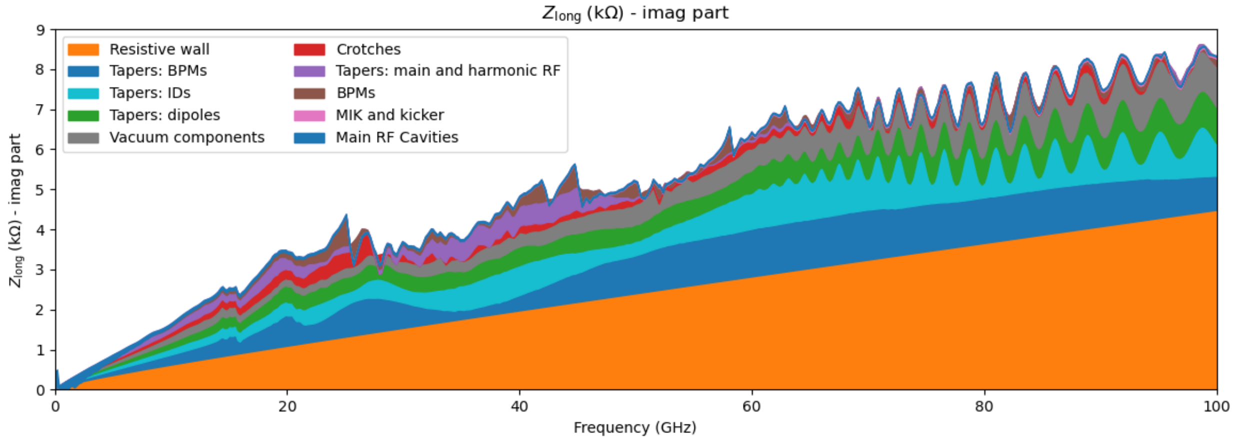
$$\alpha_c = 1.0695 \times 10^{-4}$$

$$\alpha_2 = 6.15 \times 10^{-4}$$

$$\alpha_3 = -19.2 \times 10^{-4}$$

- Impedance model included:

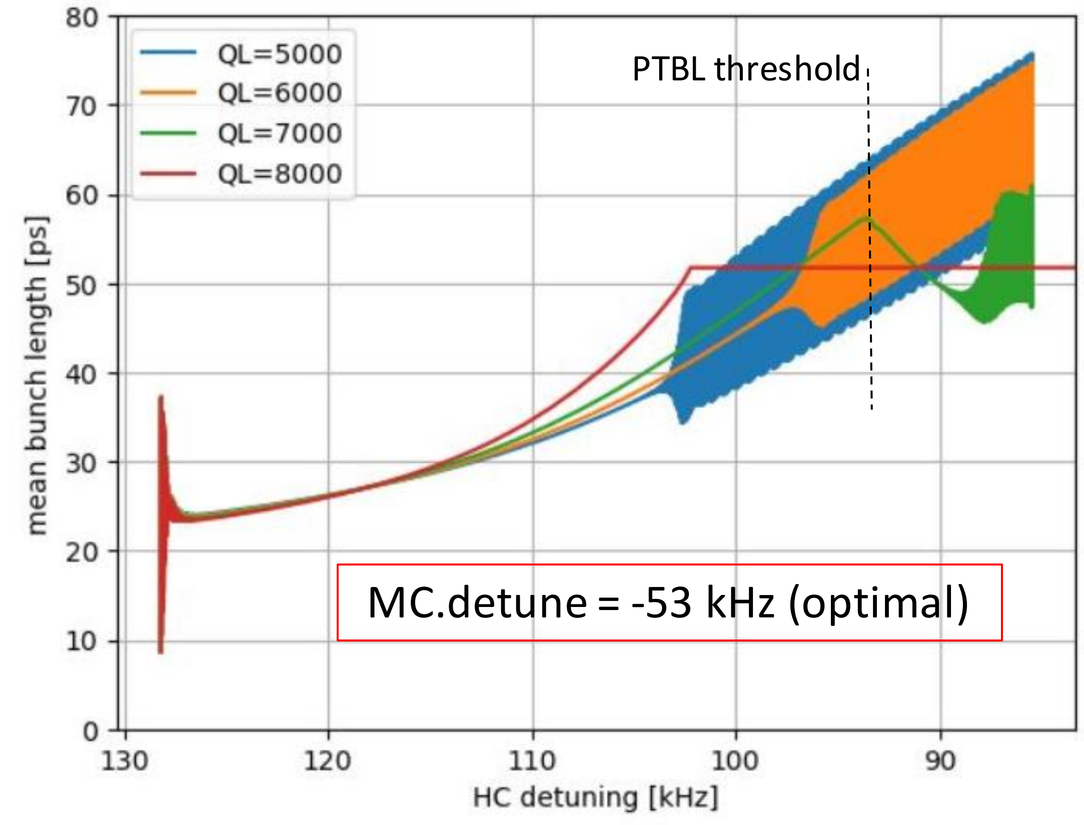


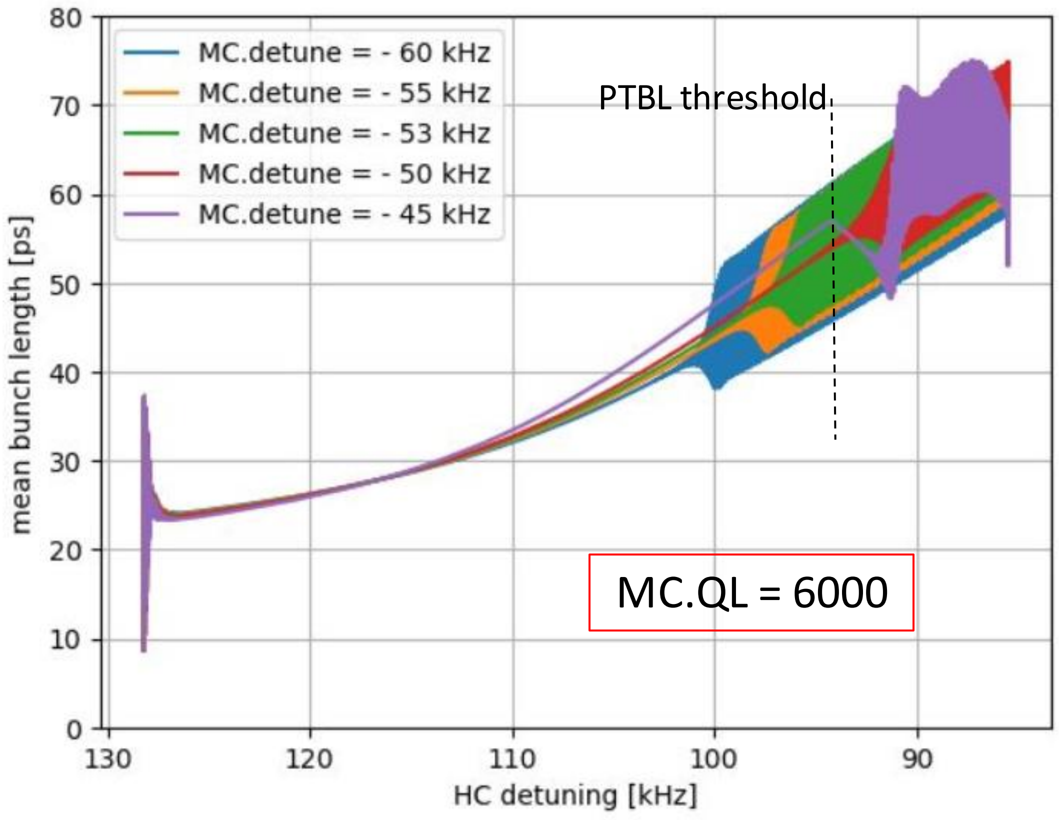





[1] Gamelin, A., Foosang, W., & Nagaoka, R. mbtrack2, a Collective Effect Library in Python. IPAC'21
[2] https://gitlab.synchrotron-soleil.fr/PA/collective-effects/mbtrack2

# Results w/o FB in uniform filling at 500 mA




Depending on the main cavity (MC) parameters, different instabilities are limiting the bunch lengthening:

- The fast mode coupling instability (dipole-quadrupole mode merging)
- The coupled bunch l = 1 instability (PTBL)

A large bunch lengthening factor (> 55 ps RMS) can still be obtained at the price of non-optimal MC parameters (increased reflected power).


[1] Bosch, R. A., Kleman, K. J., & Bisognano, J. J. (2001). Robinson instabilities with a higher-harmonic cavity. *Physical Review Special Topics-Accelerators and Beams*, *4*(7), 074401.
[2] 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.
[3] He, T., Li, W., Bai, Z., & Wang, L. (2022). Periodic transient beam loading effect with passive harmonic cavities in electron storage rings. *Physical Review Accelerators and Beams*, *25*(2), 024401.

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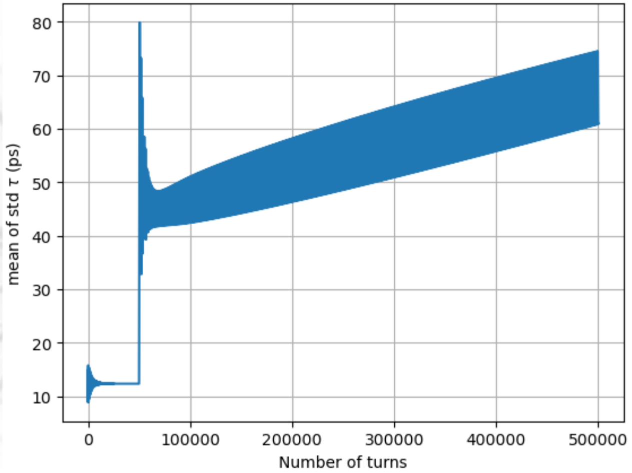
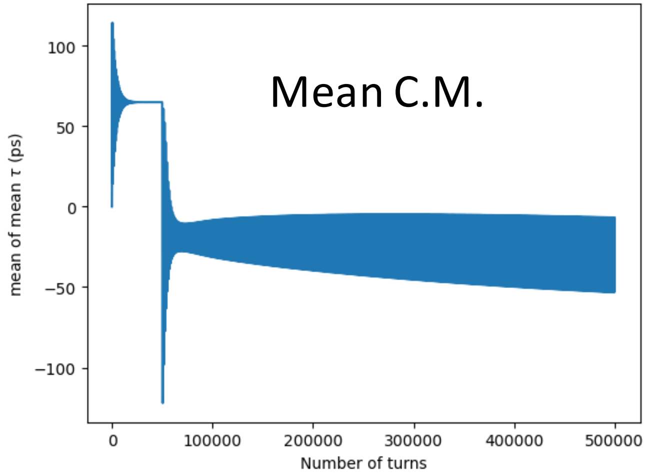
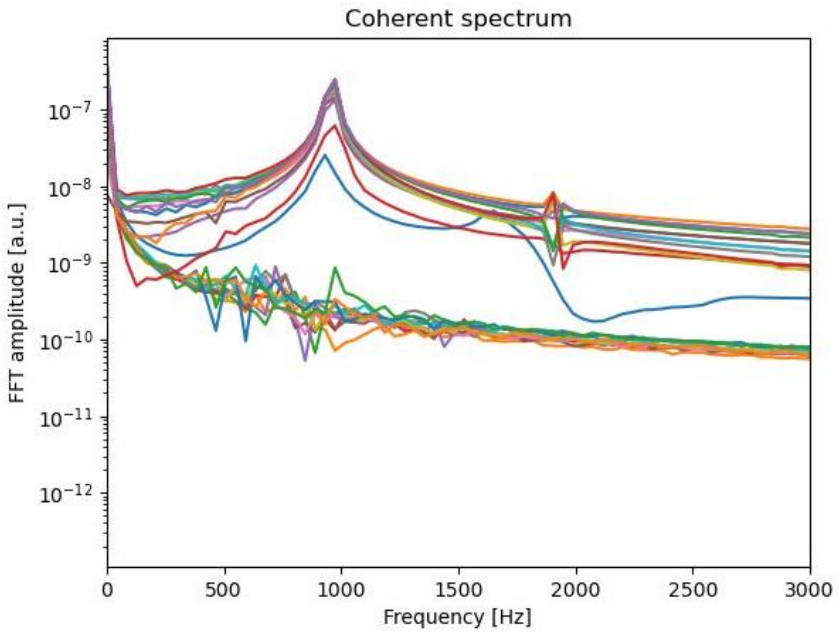
# Fast mode coupling instability

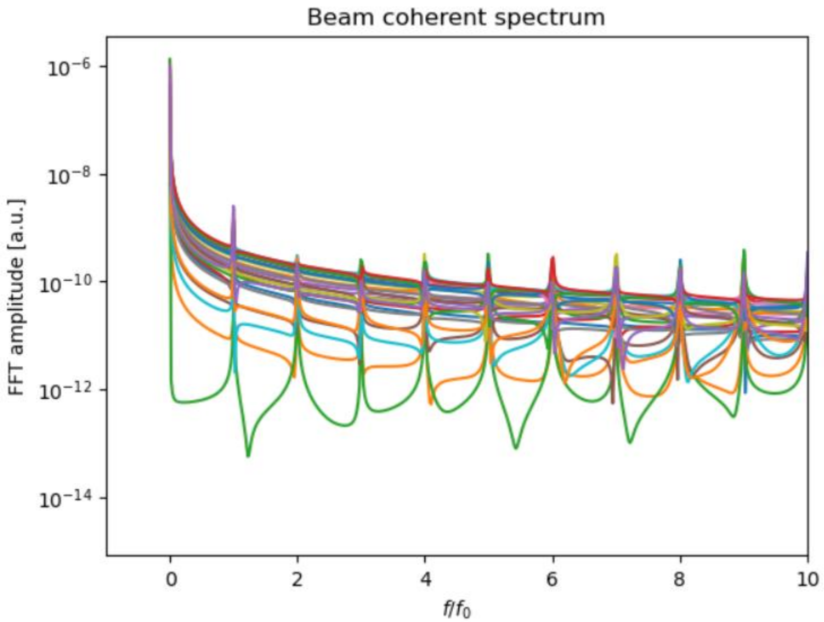
Some characteristic of this fast mode coupling instability:

- Dipole-quadrupole (m=0 & m=1) oscillations at ~ 970 Hz
- Coupled bunch mode l = 0
- The instability is not observed when integrating the equation of motion (h rigid bunch model) => the quadrupolar oscillation is a cause not an indirect consequence.



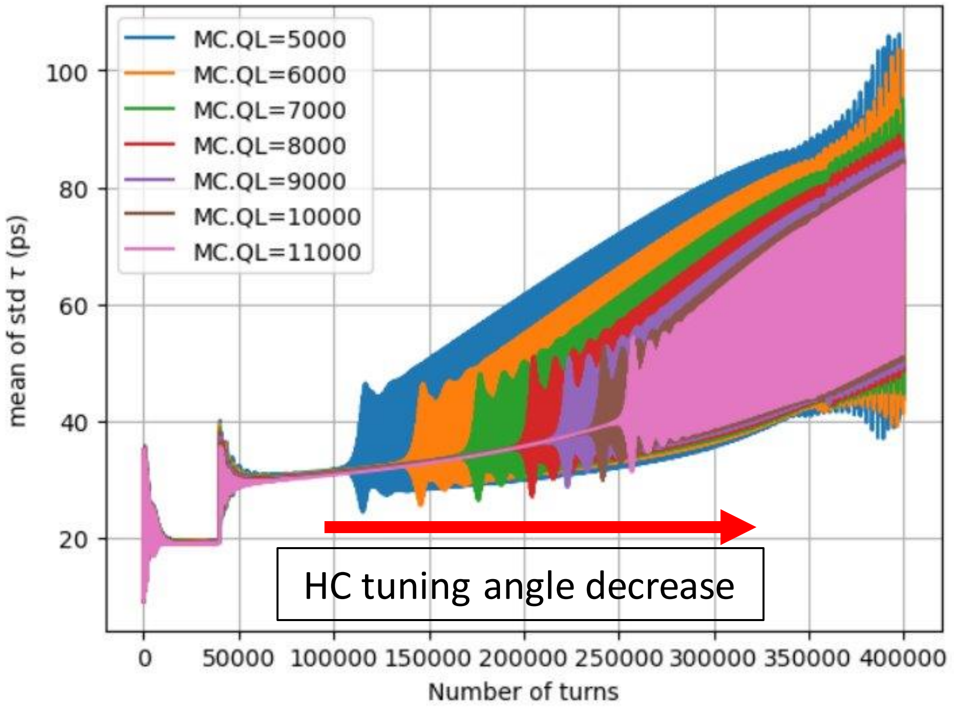



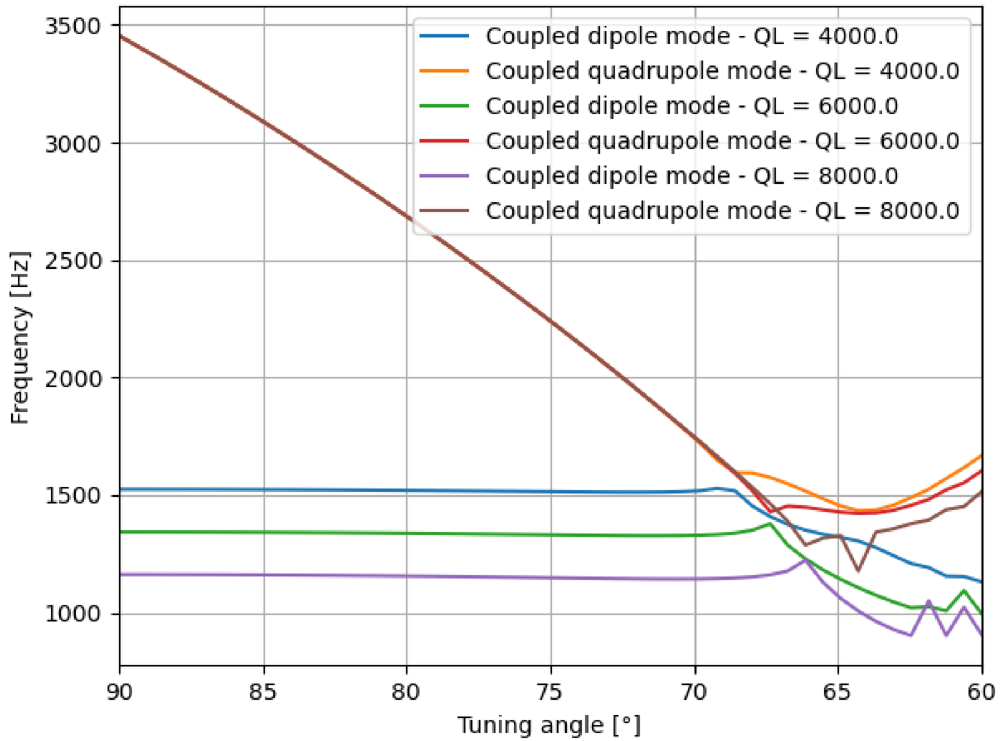
# Results w/o FB in 32 bunch mode at 200 mA

At 200 mA, the bunch lengthening is strongly limited by the fast mode coupling instability (dipole-quadrupole):

Tracking (mbtrack2)




Bosch theory




- Increasing the main cavity loaded Q factor also helps at 200 mA but does not prevent the fast mode coupling instability.
- Note that loaded Q factor values above 7000 are not practical as they would lead to too much reflected power.


Bosch, R. A., Kleman, K. J., & Bisognano, J. J. (2001). Robinson instabilities with a higher-harmonic cavity. *Physical Review Special Topics-Accelerators and Beams*, *4*(7), 074401.

# Proportional Integral loop

This "slow" loop use a Proportional Integral (PI) controller to control a cavity amplitude and phase via generator current Ig to take into account the cavity response.

Important parameters are:

- gain = [0.01,1000] # Proportional gain (Pgain) and integral gain (Igain) of the feedback
- sample_num = 208 # 1.69 MHz // 0.59 µs - Number of bunch over which the mean cavity voltage is computed.
- every = 208 # 1.68 MHz // 0.59 µs - Update rate of the FB (time interval between two cavity voltage monitoring and feedback).
- delay = 704 # 0.5 MHz // 2 µs - Loop delay of the PI feedback system.

This loop is comparable with what is in operation in SOLEIL today but:

- Independent loops for amplitude/phase.
- Probably faster feedback update rate (~3 RF buckets)
- Will be replaced by IQ (in phase, in quadrature) FB for SOLEIL II.

Pseudo code:

During the `CavityResonator.track` call, at each `every` RF bucket:

- The `cavity_phasor` is computed as the mean over `sample_num` buckets.
- The following calculation are done:
  - `diff = (Vc*exp(1j*theta) - cavity_phasor) - FFconst` where `FFconst` is the feedfoward constant.
  - `I_record = I_record + diff/fRF` where `fRF` is the RF frequency.
  - `FB_val = Pain * diff + Igain * I_record`
  - `Ig = Vg2Ig(FB_val) + FFconst` where `Vg2Ig` is a function to go from generator voltage to generator current.
- `Ig` is applied after `delay` RF buckets.
- `Ig` is then transformed back to generator voltage and modifies `Vg` and `theta_g`.

See [1] for the description on how to go from `Ig` to `Vg` and opposite.

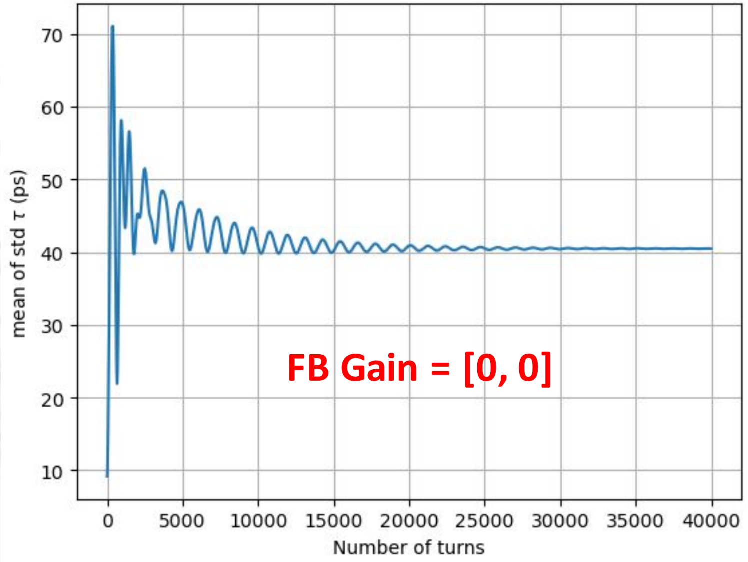
RF feedback implementation in mbtrack2: N. Yamaoto/A. Gamelin

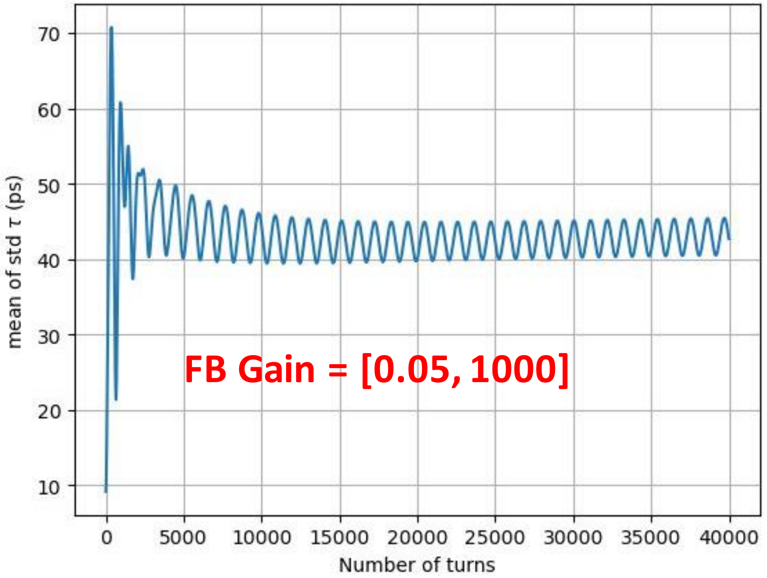
[1] Yamamoto, N., Gamelin, A., Marchand, P., Nagaoka, R., Sakanaka, S., & Yamaguchi, T. Stability survey of a double rf system with rf feedback loops for bunch lengthening in a low-emittance synchrotron ring. *Proceedings of the IPAC2023, Venice, Italy.*
[2] Yamamoto, N., Takahashi, T., & Sakanaka, S. (2018). Reduction and compensation of the transient beam loading effect in a double rf system of synchrotron light sources. PRAB, 21(1), 012001.
[3] Akai, K. (2022). Stability analysis of rf accelerating mode with feedback loops under heavy beam loading in SuperKEKB. PRAB, 25(10), 102002.

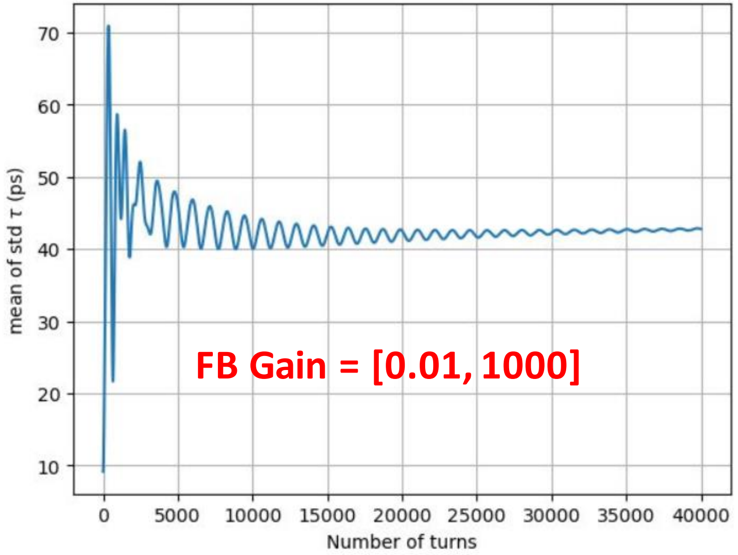
**Fixed parameters:**
- Vc = 1,6 MV
- QL = 6000
- MC.detune = Optimal (-58 kHz)
- HC.detune = 110 kHz

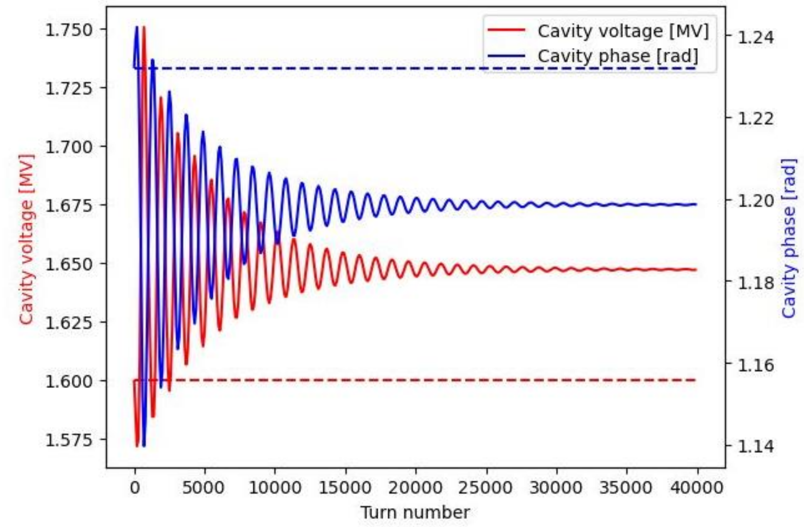
# Proportional Integral loop

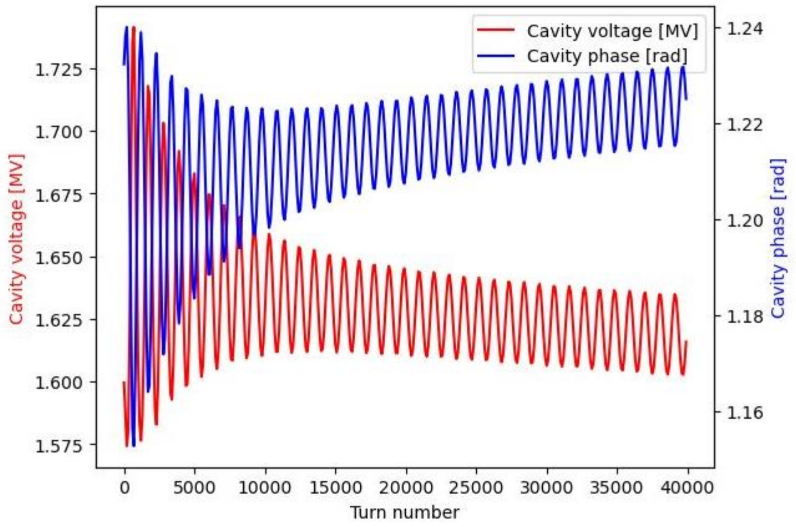
**The PI loop can trigger the fast mode coupling instability by itself. Reducing only the proportional gain makes it less sensitive to the DQ oscillations at 970 Hz.**

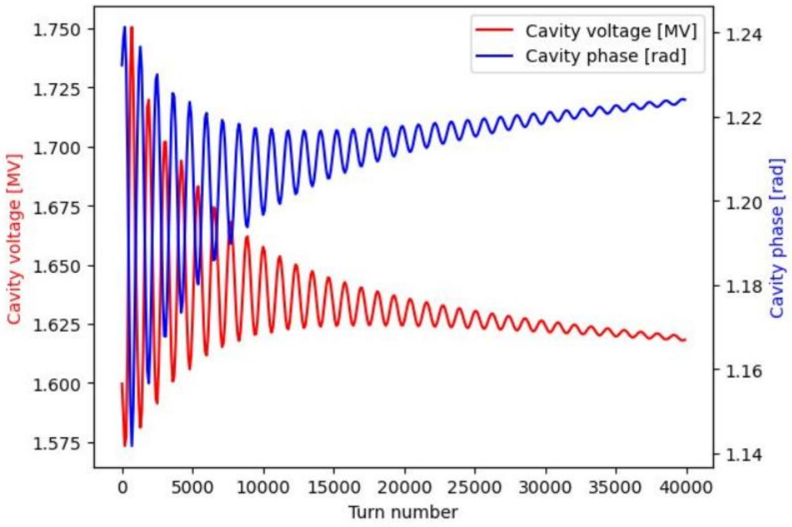


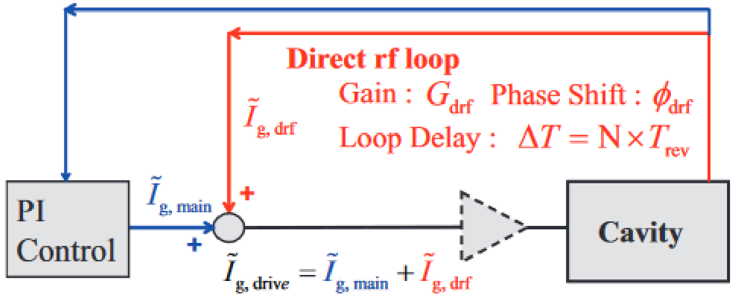



# Direct RF Feedback

The direct RF feedback (DFB) aims to reduce the effective shunt impedance Rs seen by the beam to fight against instabilities. It works by inducing a new generator voltage component which is opposite to the beam loading contribution.

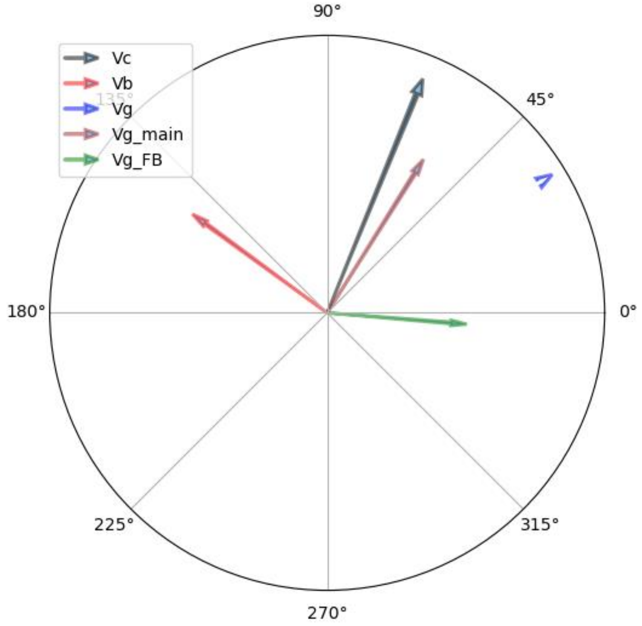
Important parameters are:

- gain = 0.1 at 500 mA // up to 0.6 at 200 mA # Gain of the DFB
- phase_shift = 0 # Phase shift of the DFB
- sample_num, every and delay as for the PI loop




**Rs = 20 MΩ** → **Rs = 18 MΩ for gain = 0.1**

**Rs = 9.6 MΩ for gain = 0.6**




This loop is similar to what is in operation in SOLEIL today but:

- With much higher gain because of SC cavity, probably a reduction of the shunt impedance Rs by a factor 3 is fine for NC.
- Will be replaced by IQ (in phase, in quadrature) FB for SOLEIL II.

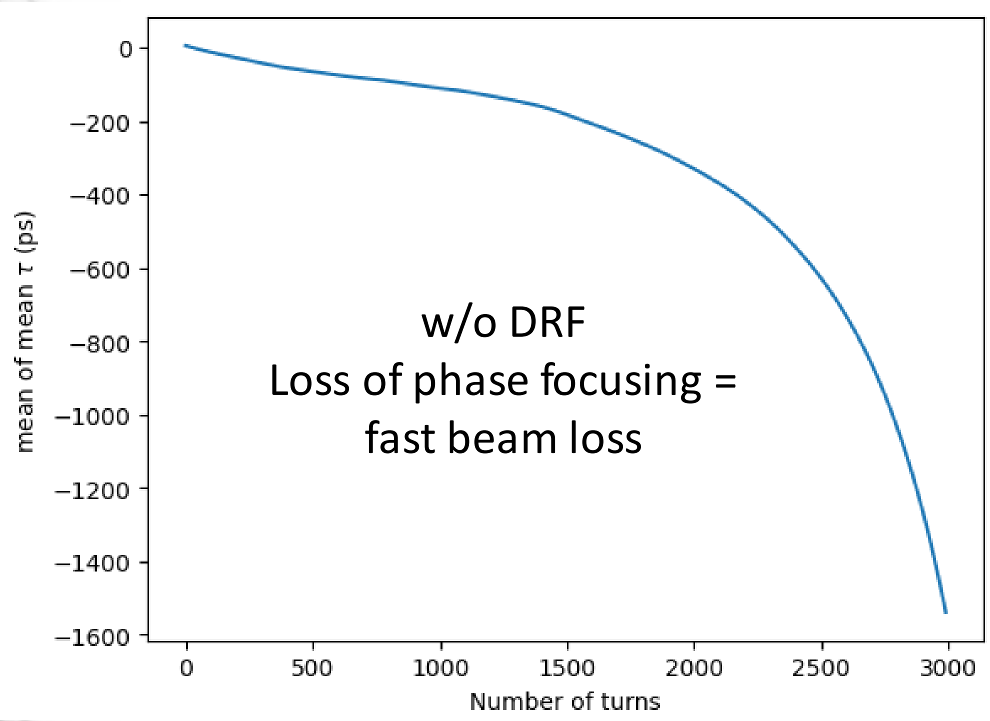
Pseudo code:

During the `CavityResonator.track` call, at each `DFB_every` RF bucket:

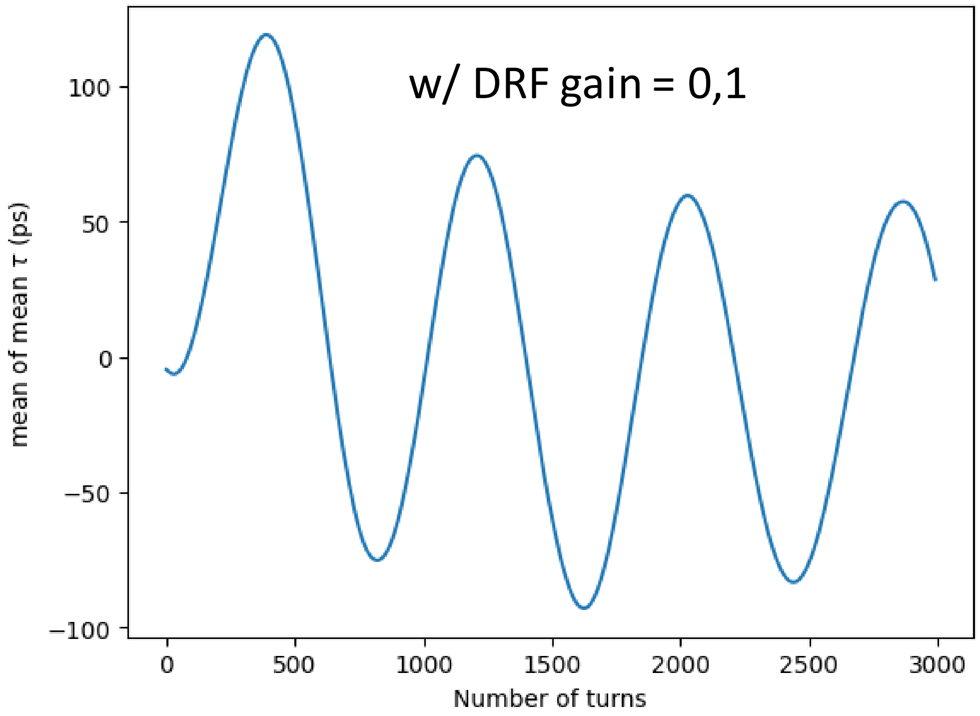
- The `cavity_phasor` is computed as the mean over `DFB_sample_num` buckets.
- The following calculation are done:
  - `Vg_DFB = DFB_gain * cavity_phasor * exp(1j*DFB_phase_shift)`.
  - `Ig_DFB = Vg2Ig(Vg_DFB)` where `Vg2Ig` is a function to go from generator voltage to generator current.
- `Ig_DFB` is applied after `DFB_delay` RF buckets.
- The total `Ig` is then transformed back to generator voltage and modifies `Vg` and `theta_g`.

Benchmark of the usual DC Robinson instability (what the DFB is used for at SOLEIL today) using “toy” model:

$R_s = 20\ M\Omega$ – theory predict DC Robison unstable



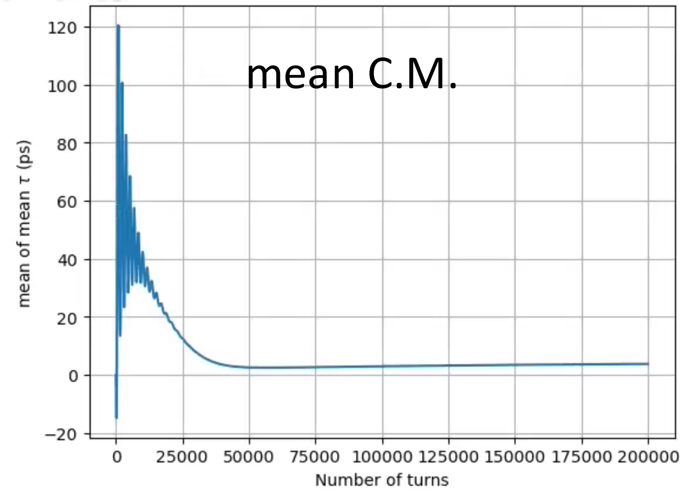

$R_s$ reduced by DFB to $19{,}6\ M\Omega$ – theory predict DC Robison stable

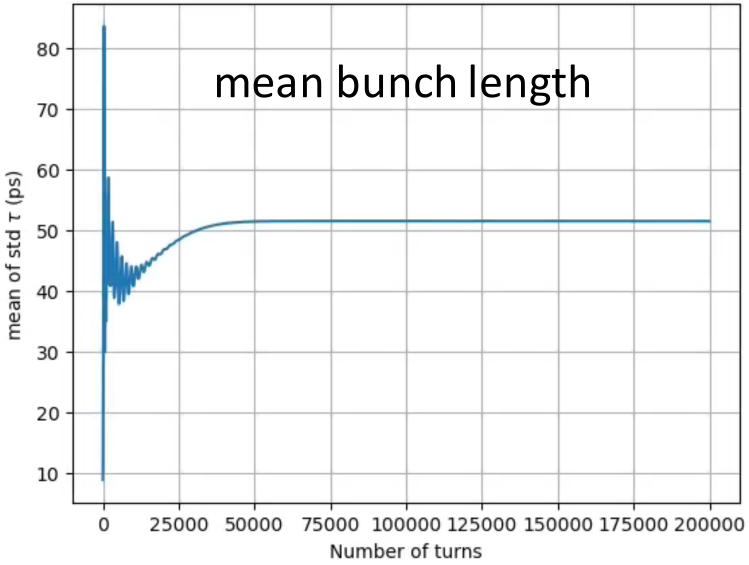


**Fixed parameters:**

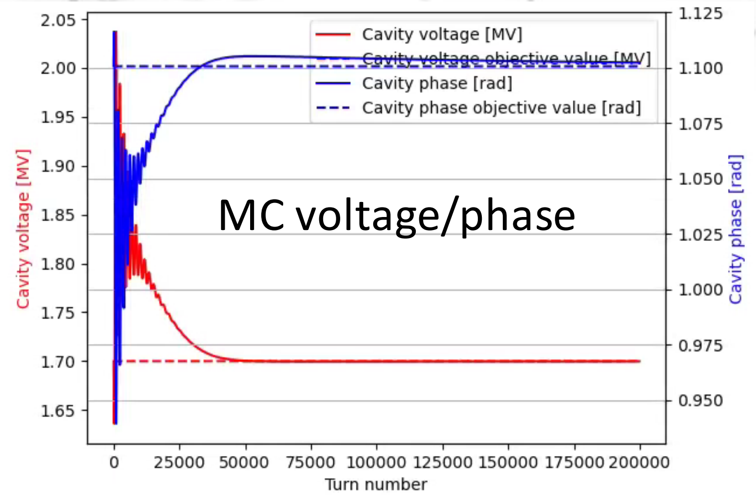
- Vc = 1,7 MV
- QL = 6000
- MC.detune = Optimal
- HC.detune = 102.5 kHz
- PI_gain = [0.01,1000]
- DFB_gain = 0,1
- IDs closed

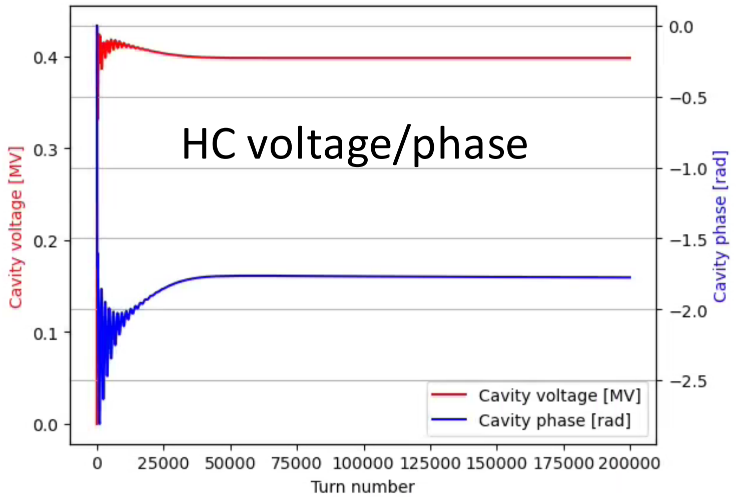
# Results in uniform filling at 500 mA with feedbacks

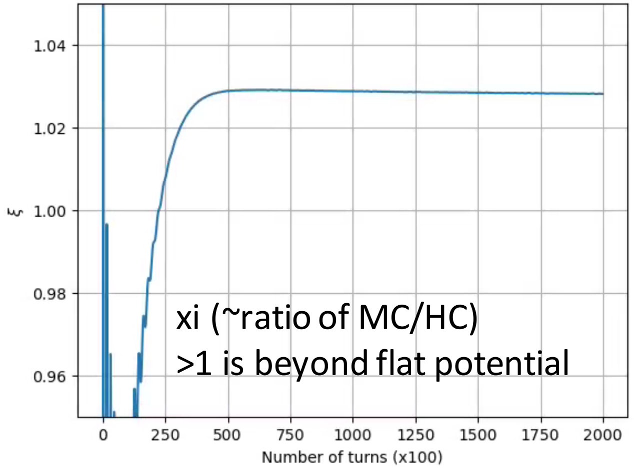



- ➢ Direct RF FB allows to recover best performances without increasing QL or moving from optimal tuning.
- ➢ Bunch lengthening limit is no longer fast mode coupling instability (no DQ oscillation) but coupled bunch l=1 instability (PTBL).
- ➢ With this parameters, the maximum bunch length is ~51 ps RMS
- ➢ With open IDs, performance is slightly better ~54 ps as the PTBL threshold is further away.



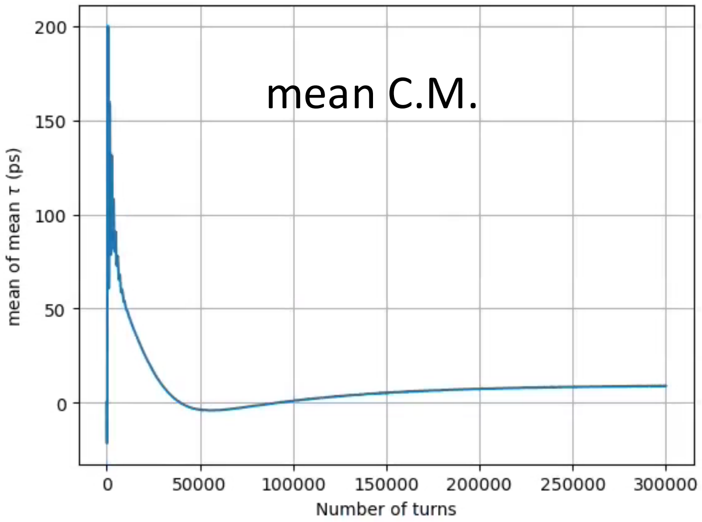



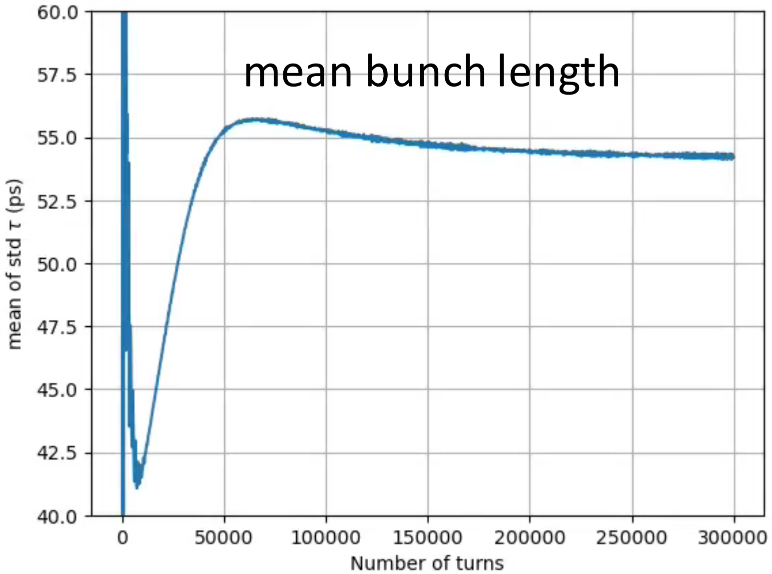
**Fixed parameters:**

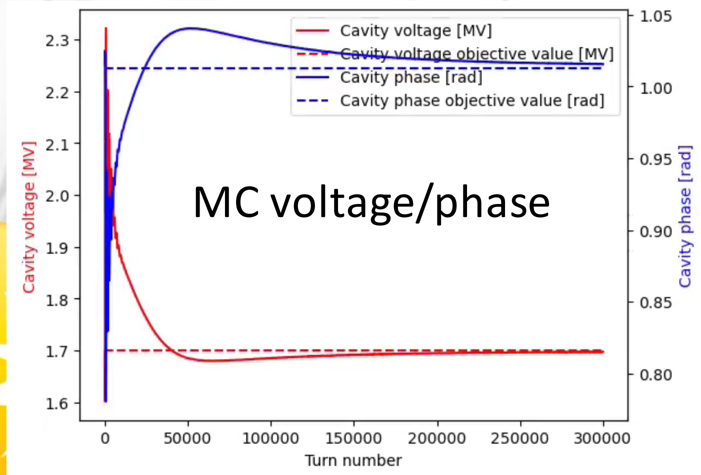
- Vc = 1,7 MV
- QL = 6000
- MC.detune = Optimal
- HC.detune = 36.2 kHz
- PI_gain = [0.01,1000]
- DFB_gain = 0.55
- IDs closed

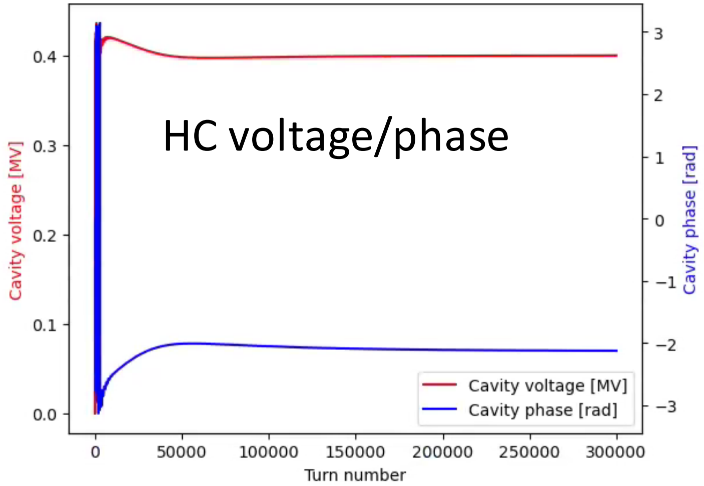
# Results in 32 bunch mode at 200 mA with feedbacks

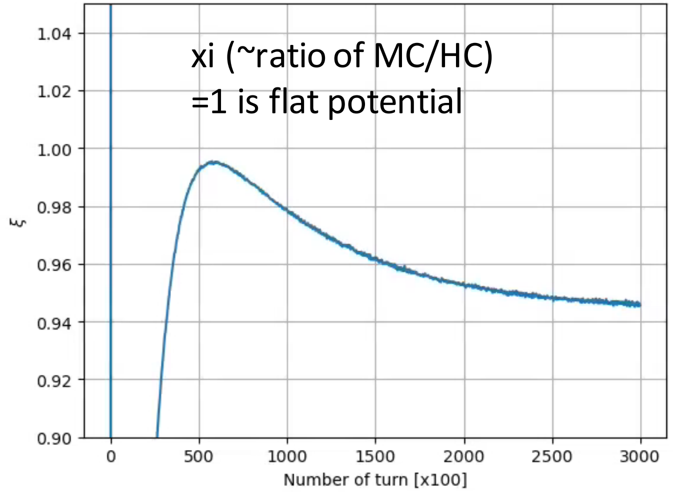
- The fast mode coupling instability is stronger at lower current, so a DFB gain of 0.55 is needed to stabilize the beam close to the flat potential conditions.
- Stonger DFB gain seems to lead to unstable beam (in less than ~ 1000 turns). It is not fully clear if this is a numerical or physical issue for now.
- Fast mode coupling instability is still the limiting factor to get closer to FP conditions. The maximum bunch length is ~54 ps RMS.
- With open IDs, performance is slightly better ~58 ps as a DFB gain of 0.6 can be used in a stable way.



# Conclusion

Even considering SC passive HC, not much Touschek lifetime was gained using HC in high current per bunch much modes:

- Initial bunch length is already quite large due to impedance
- HC also reduces emittance and energy spread growth induced by IBS + SC + MWI
- Probably the same with NC active HC

Now, refocusing our working range for the HC on the 200 mA to 500 mA region:

- Switch to 4th NC passive HC (~4 times less expensive than SC passive HC)
- Limited by fast mode coupling instability (dipole-quadrupole oscillations)
- Using a direct RF FB (or probably also a mode 0 damper like in MAX IV) on the main cavity allows to achieve more bunch lengthening at 200 mA and 500 mA:
    - still limited by fast mode coupling at 200 mA
    - and limited by PTBL at 500 mA
- Performances achieved considering RF FBs are comparable to the 4th SC passive HC (but lower than 3rd SC passive HC)

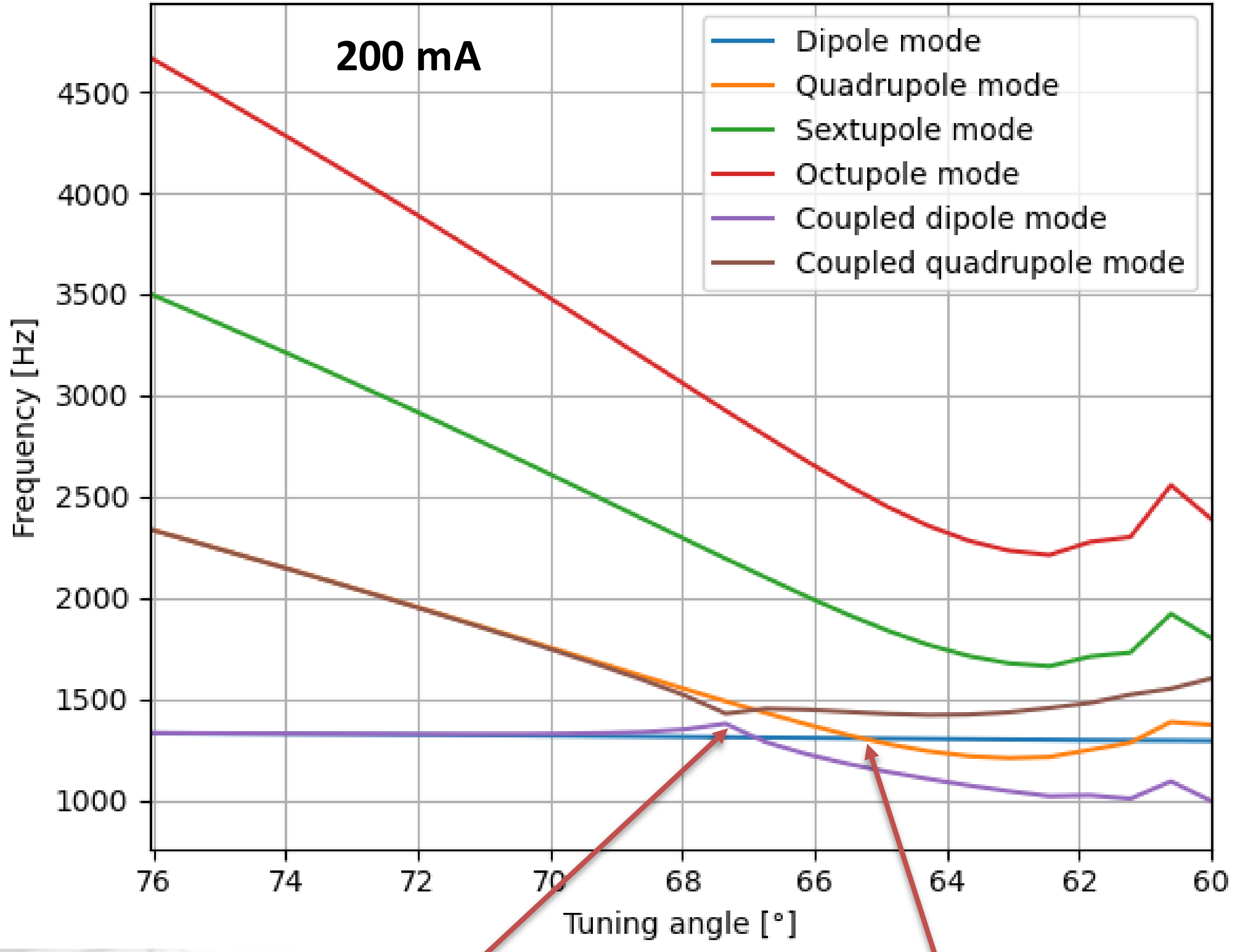
Jupyter notebook with examples for FB FB in mbtrack2:
https://colab.research.google.com/github/GamelinAl/mbtrack2_examples/blob/main/mbtrack2_RF_feedback.ipynb

Many thanks to colleagues for their collaboration to this studies, in particular:

- The whole SOLEIL II team
- ESRF RF group
- N. Yamamoto (KEK)
- T. Olsson (HZB)

# Backup slides

# Fast mode coupling instability



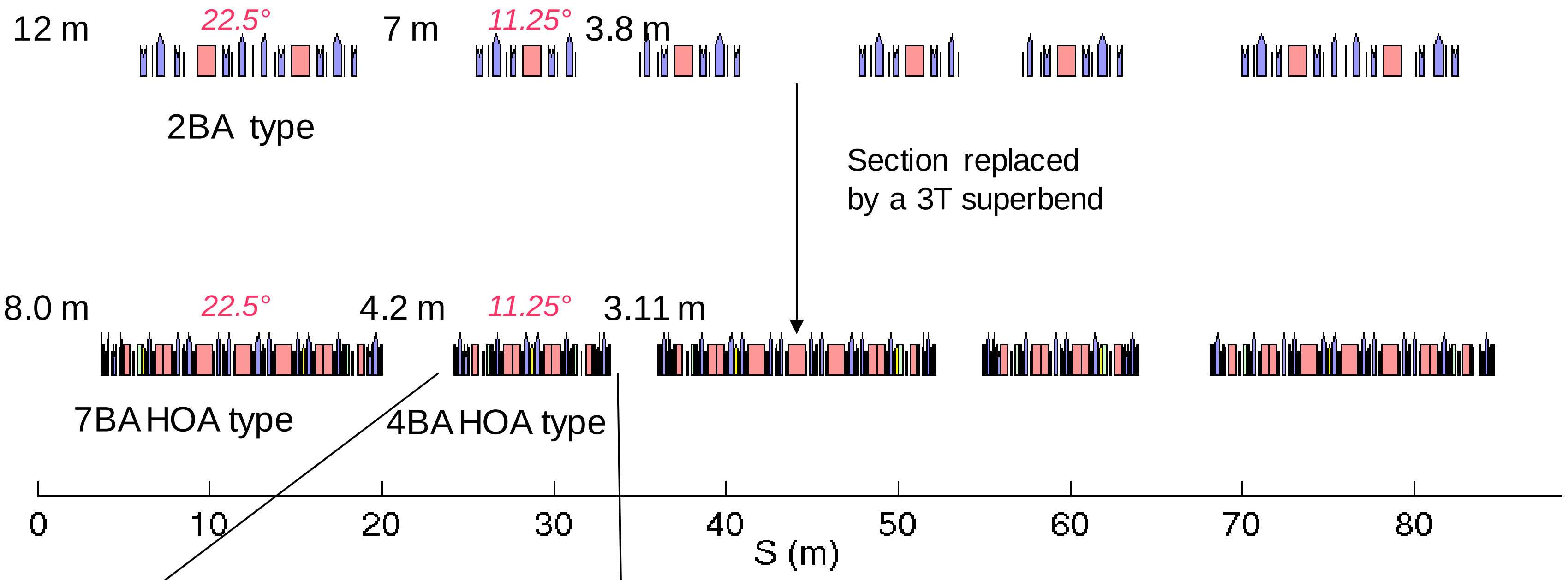

- Mode coupling decreases the threshold of the dipole-quadrupole instability.
- Most of the time no instability is seen if mode coupling is neglected for SOLEIL II parameters

Dipole-Quadrupole instability considering mode coupling
(= fast mode coupling instability)

Dipole-Quadrupole instability w/o considering mode coupling

Bosch, R. A., Kleman, K. J., & Bisognano, J. J. (2001). Robinson instabilities with a higher-harmonic cavity. *Physical Review Special Topics-Accelerators and Beams*, *4*(7), 074401.

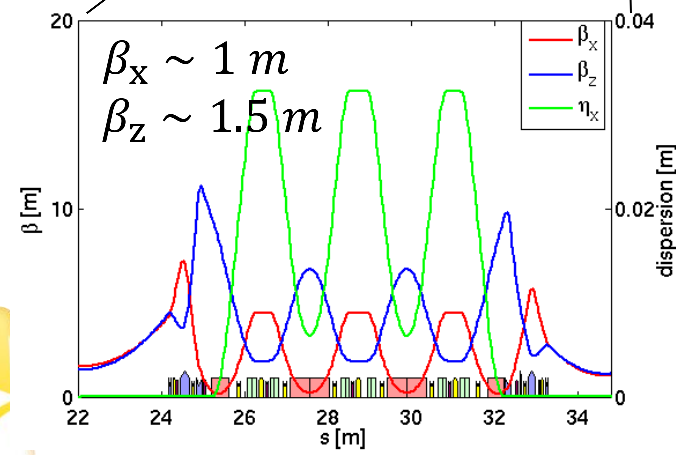
# SOLEIL II




**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

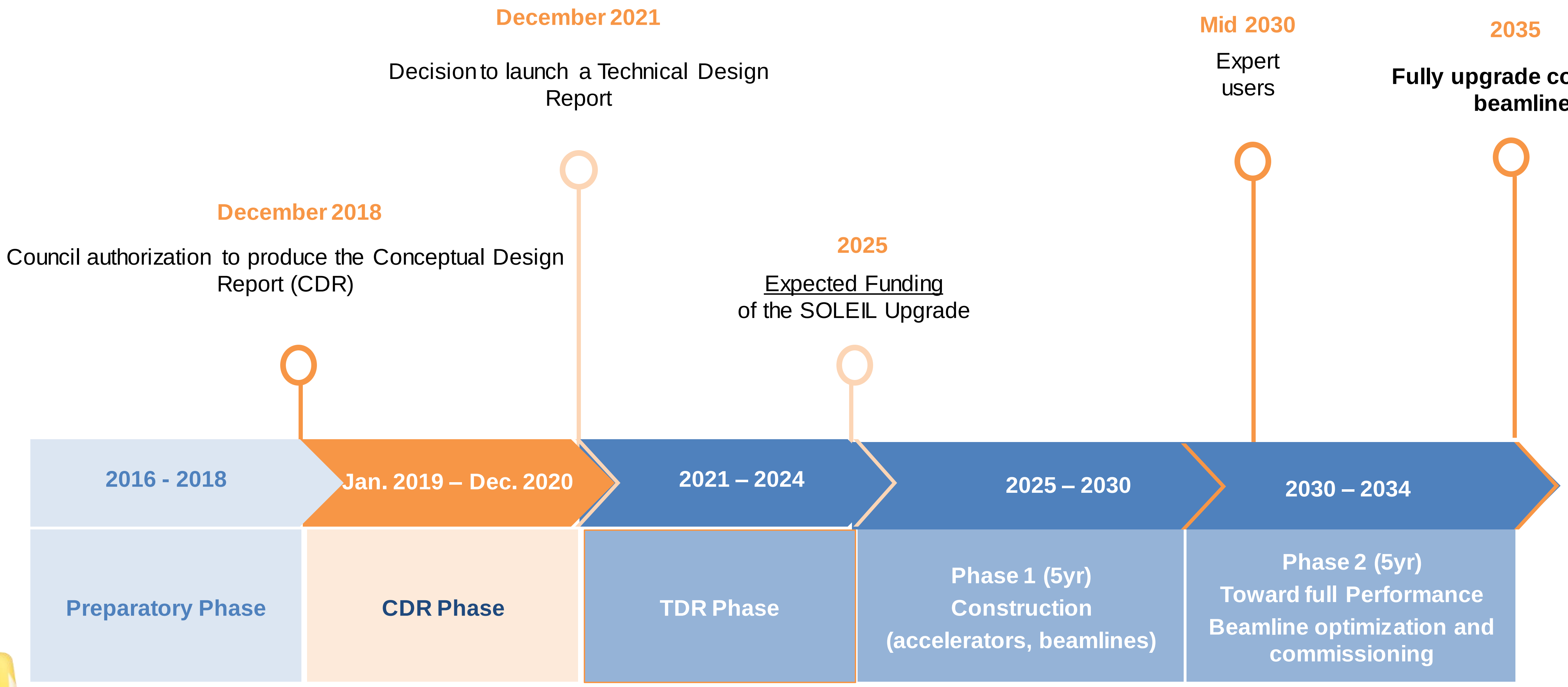
| | Present | SOLEIL II |
|---|---|---|
| H-Emittance (2.75 GeV) | 4 nm.rad | 84 pm.rad |
| Circumference | 354.10 m | 353.97 m |
| Straight section number | 24 | 20 |
| Long straight length | 12.00 m | 8.00 / 9.00 m |
| Medium straight length | 7.00 m | 3.60 / 4.20 m |
| Short straight length | 3.80 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 |




<u>Major features of the upgrade:</u>

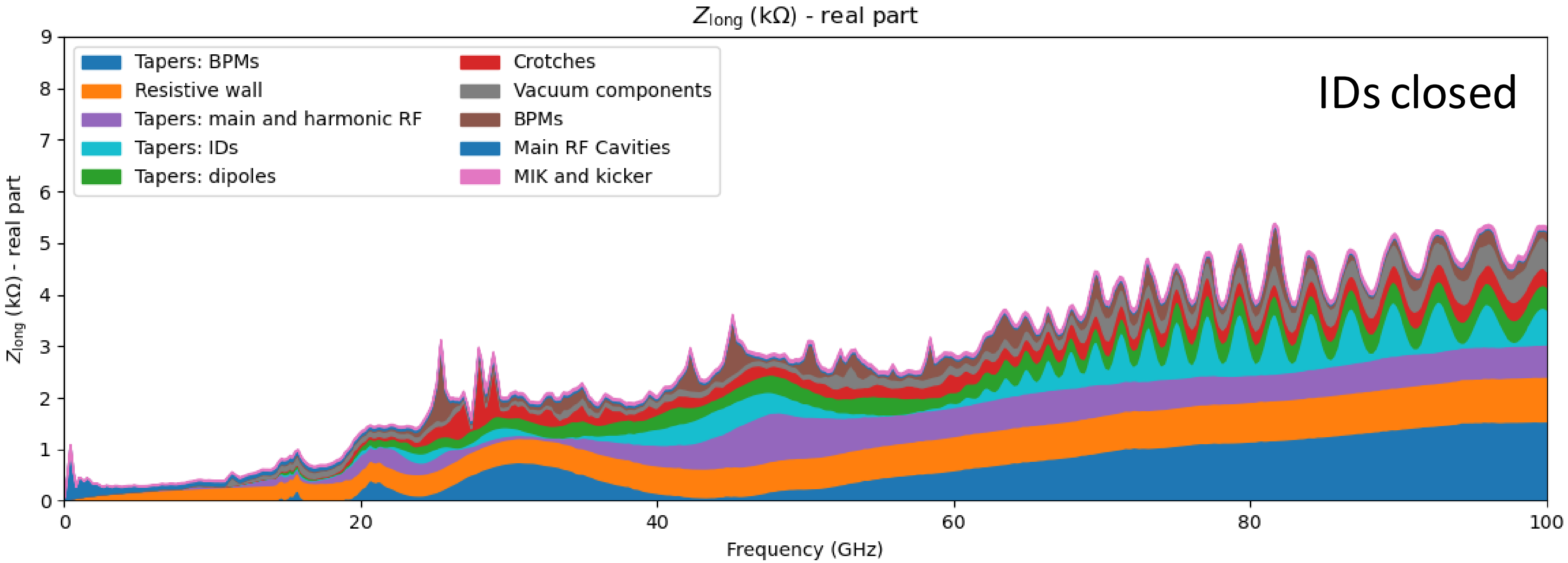
- Fit "at best" the beamlines positioning
- Permanent magnets for dipoles, quadrupoles and reverse bends
- Energy saving
- Standard beam pipe inner diameter of 12 mm
- 95 % NEG coated ring
- Off axis injection (using MIK)
- Beam lifetime of ~ 3 hrs w/o HC

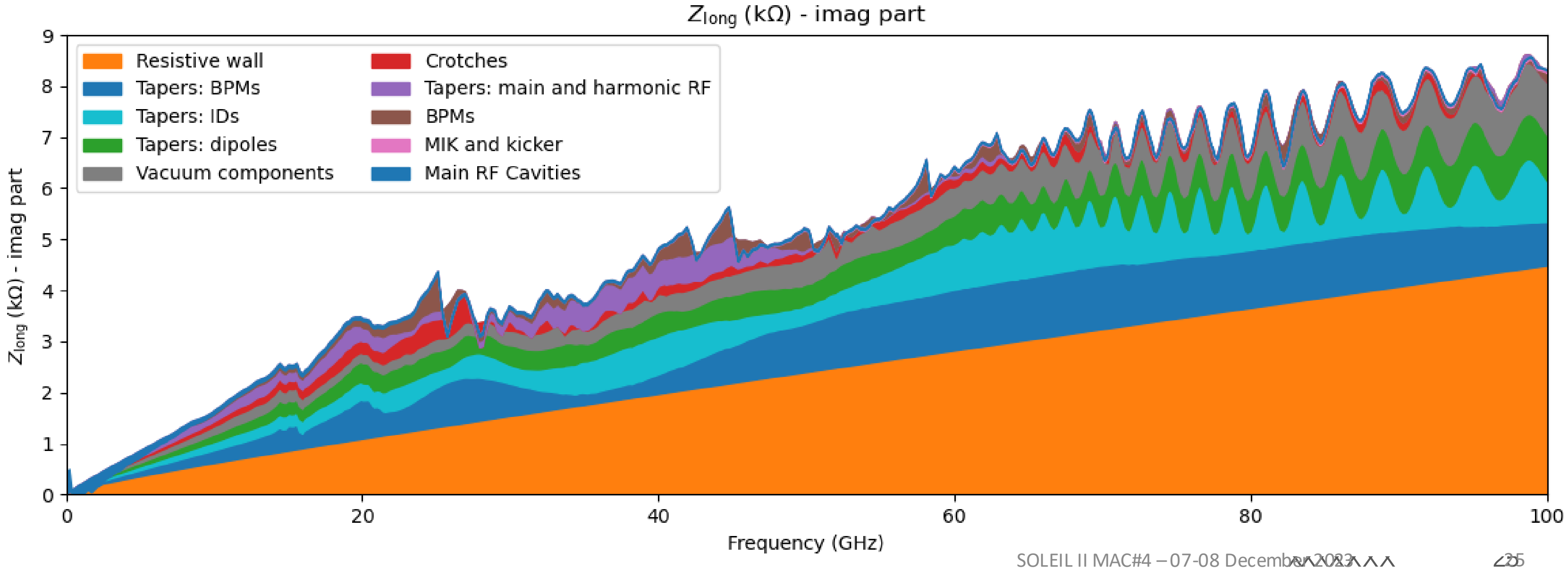
# SOLEIL II




**For now, the first two years of the project (2024/2025) are funded up to 38M€.**

# Impedance model TDR2.1 - Longitudinal impedance




- Overall impedance is a little bit higher compared to TDR2 model as new components were added (ID tapers in light blue).
- IDs open/close affect mainly the vertical impedance.
- As the chamber is mostly round, the horizontal impedance (with or without IDs) is very close to vertical impedance with ID opened.

# Single bunch tracking