HARMONIC EU CAVITY COMISSIONING: OPERATION AND TBL COMPENSATION

HarmonLIP 2025 - Cerdanyola del Vallès, Spain

24/10/2025

Hamed Shaker on behalf of 3HC Collaboration

ALBA 3HC at BESSY-II

Table 1: Harmonic EU cavity parameters

Parameter	Value	Unit
Maximum voltage	200	kV
Shunt impedance	1.1	MΩ
Unloaded quality factor Q_0	14000	-
Tuning range	12.4	MHz

Main cavity parameters measured at the central resonance frequency, f_0.

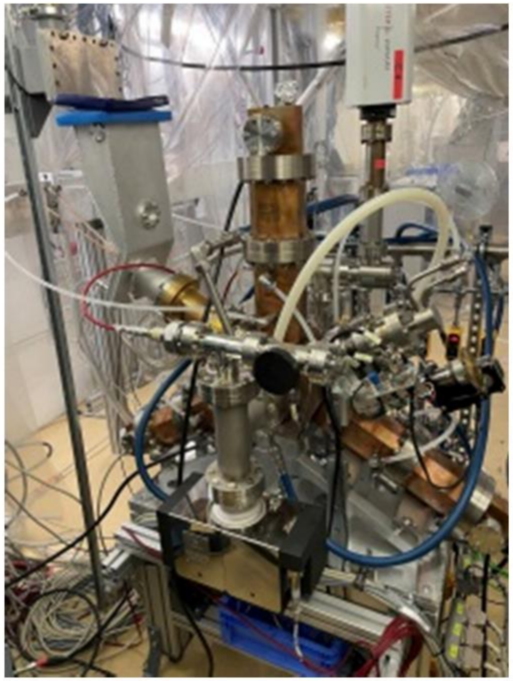
Parameter	Symbol	Value	Unit
Reflection coefficient	S_{11}	−50.8	dB
Coupling factor	β	1.006	–
Bandwidth	BW	214	kHz
Loaded quality factor	Q_l	6995	–
Unloaded quality factor	Q_0	14 031	–
Transmission to pick-up antenna	S_{21}	−45.9	dB

Input data used to calculate the impedance budgets of BESSY II.

Parameter	Symbol	Value	Unit
Revolution frequency	f_{rev}	1.2492	MHz
Beam current	I_b	300	mA
Beam energy	E	1.7	GeV
Momentum compaction factor	α	$7.3 \cdot 10^{-4}$	–
Synchrotron frequency	f_s	$7.0 \cdot 10^{3}$	Hz
Beta function	β	5.0	m
Longitudinal damping decrement	τ_s	752	s^{-1}
Transversal damping decrement	$\tau_{x,y}$	250	s^{-1}

Active harmonic EU cavity: Commissioning and operation with beam, F. Perez et al., Nuclear Instruments and Methods in Physics Research A 1072 (2025) 170195
And Summary of the commissioning of the active harmonic EU cavity, F. Perez et al., IPAC24, US

3HC collaboration



A collaboration between ALBA, HZB and DESY. ALBA 3HC cavity and LLRF installed in BESSY-II since 2022 and dismantled on August 2025.
Some recent achievements:

- TBL compensation
- Near flat potential operation
- Passive loop operation

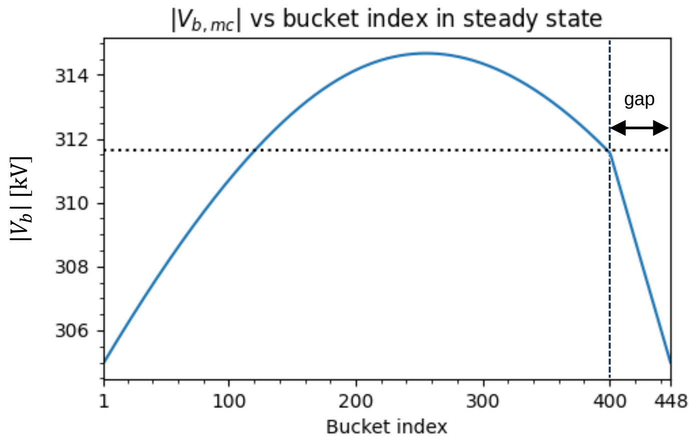
TRANSIENT BEAM LOADING (TBL)

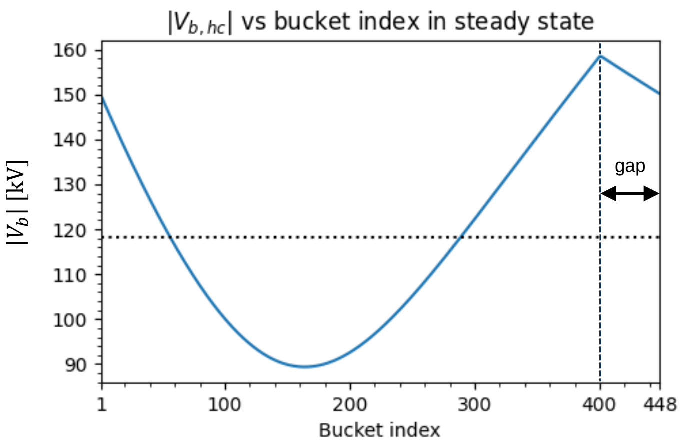
- In RF cavities, the **beam induced voltage** (the beam loading), V_b represents a considerable part of the total voltage, V_c. This contribution can be around the 40% in the MC and > 80% in the HC

- V_b is built on the **successive passage** of bunches. It reaches an **equilibrium** when the decay of the cavity voltage between bunch passages matches the voltage added by each bunch

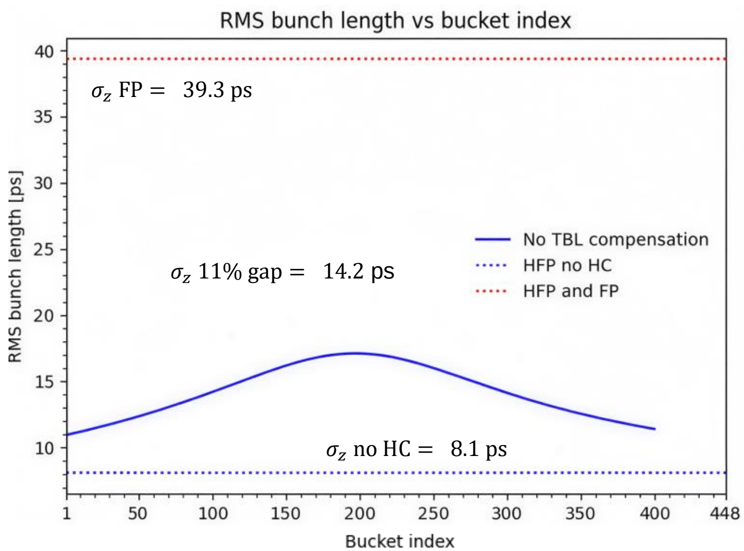
$$V_b = -\left(\frac{1}{2}\, V_{b0} + V_{b1}\, e^{-\frac{t_1}{\tau_f}}\, e^{i\psi_1} + V_{b2}\, e^{-\frac{t_2}{\tau_f}}\, e^{i\psi_2} + \cdots\right) = -\frac{1}{2}\, V_{b0} - \sum_{l=1}^{N} V_{b0}\, e^{l(-\delta + i\psi)}$$

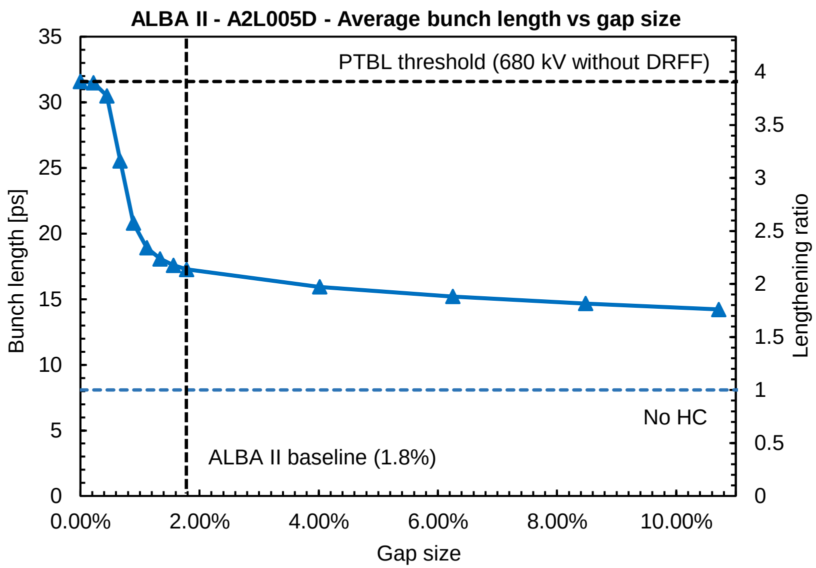
- **Uneven charge distribution** in the buckets, such as gaps, break the homogeneous build-up causing a periodic modulation in the cavity voltage with a period equal to the revolution time





TRANSIENT BEAM LOADING (TBL)





- The **different MC and HC voltages** seen by the bunches cause different bunch properties (synchrotron frequency, bunch length, phase, etc.) along the bunch train
- The bunch length, and thus the **Touschek beam lifetime**, is **specially affected** in the case of a double NC RF system tuned to maximize them
- Just a 2% gap can lead to Touschek lifetime reductions of about 45%
- Transient beam loading (TBL) **compensation** is therefore highly recommended in case a gap in the beam is foreseen

TBL COMPENSATION - METHODOLOGY

- Taking advantage of the active HCs, it is possible to modulate the generator induced voltage V_b, to **counter** the modulation induced by the beam and get a flatter cavity voltage (V_c) :

$$V_c(t) - V_b(t) = V_g(t)$$

which gives us **the ideal $\boldsymbol{V_g}$** to fully compensate the TBL. From this signal, I_g and then P_g can be then calculated [1]:

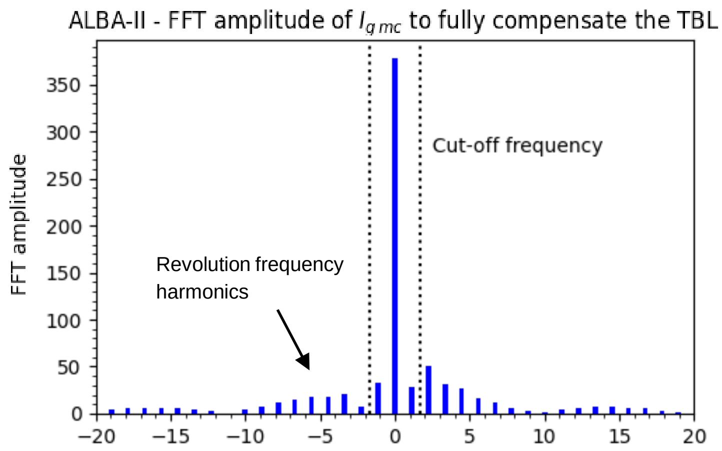
$$I_g(t) = \frac{1}{k}\left[\frac{dV_g(t)}{dt} + \frac{1}{\tau_f}[1 - i\tan\psi_d]\,V_g(t)\right] \quad \longrightarrow \quad P_g(t) = \frac{R_s\left|I_g(t)\right|^2}{8\beta}$$

- However, RF cavities have a **narrow bandwidth** and **do not accept well** the high frequency **components** of the modulated power required to fully compensate the TBL. A very **high generator** power is required for some buckets, far exceeding the available one, resulting in a high reflected power, as well

- Following the strategy proposed by [1], we **can filter out most of the high frequency components** to effectively mitigate the TBL effects with reasonable amounts of additional generator power

1. Yamamoto et al., DOI: 10.1103/PhysRevAccelBeams.21.012001

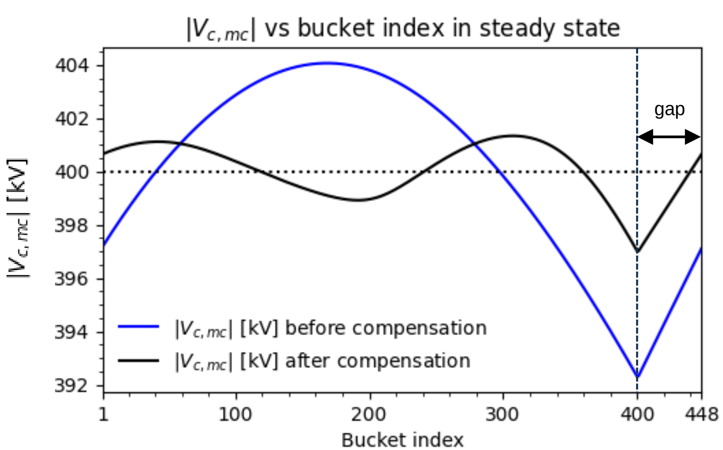
TBL COMPENSATION – METHODOLOGY

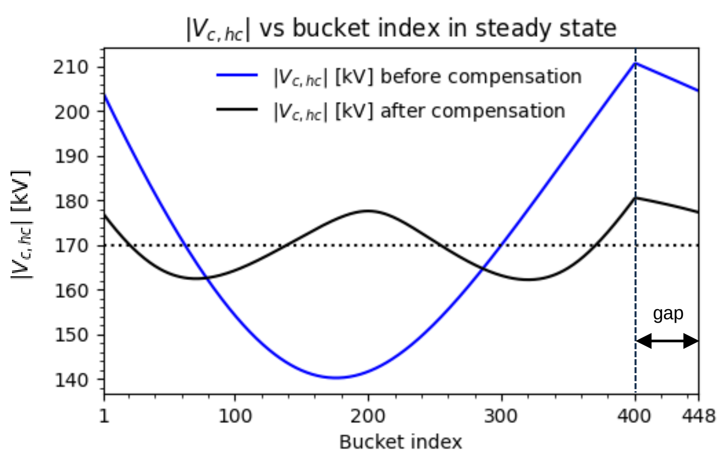


- After removing the **frequency components** higher than $\pm n f_c$, where f_c = f_{rev} (1.12 MHz for ALBA and ALBA II) we construct a new, filtered V_g :

$$V_g(t) = e^{\alpha(t-t_0)}\left[V_g(t_0) + k\int_{t_0}^{t} I_{g\,filt}\,(t')e^{-\alpha(t'-t_0)}dt'\right]$$

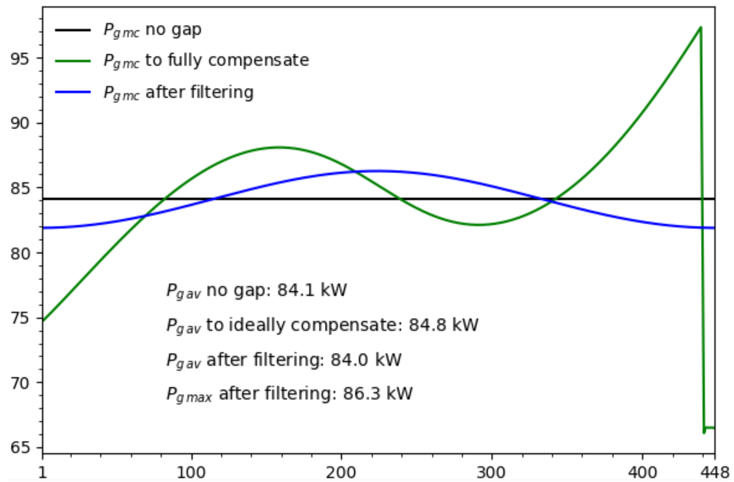
- The result is a **flatter cavity voltage signal**, both in amplitude and phase, for both the MCs and HCs, without requiring so much power:

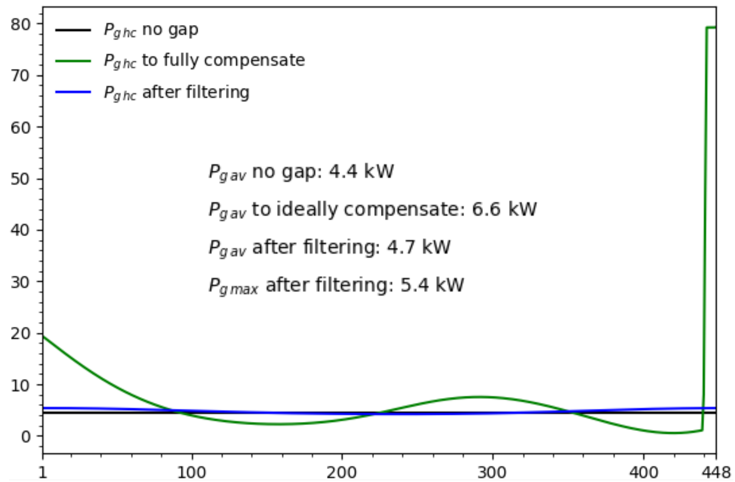




TBL COMPENSATION - METHODOLOGY

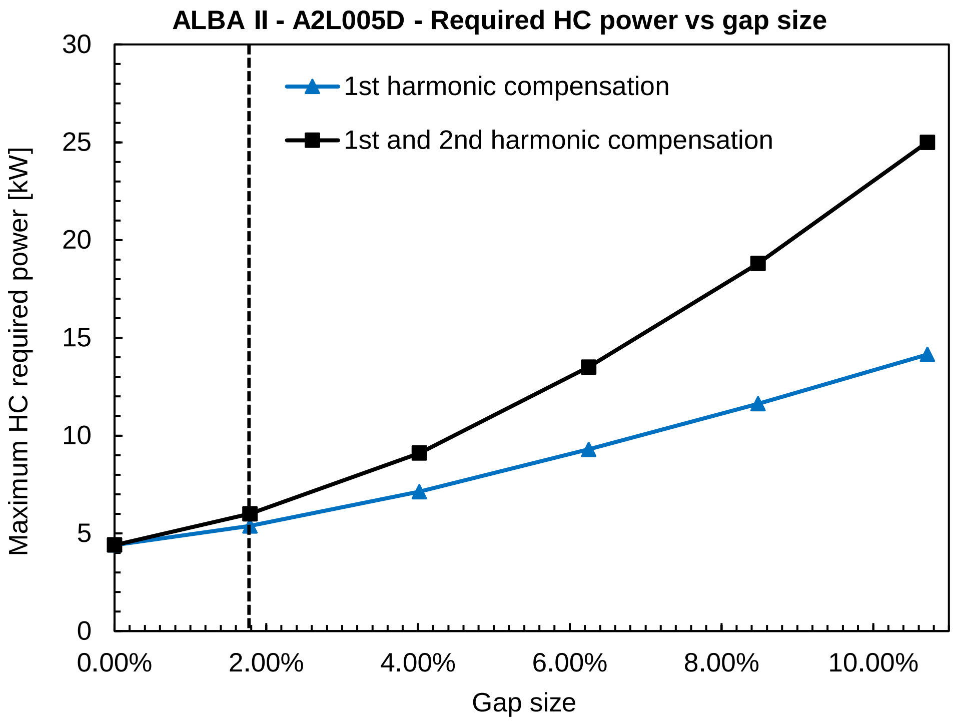
- For the ALBA II baseline scenario, for instance, full compensation in the HCs would require **80 kW of power**
- By filtering the harmonics higher than 1 f_{rev}, the required power is only 1 kW above the no-gap case, reaching a maximum of **5.4 kW**
- With the proposed compensation scheme, the average **power consumption** remains approximately **the same** as without compensation





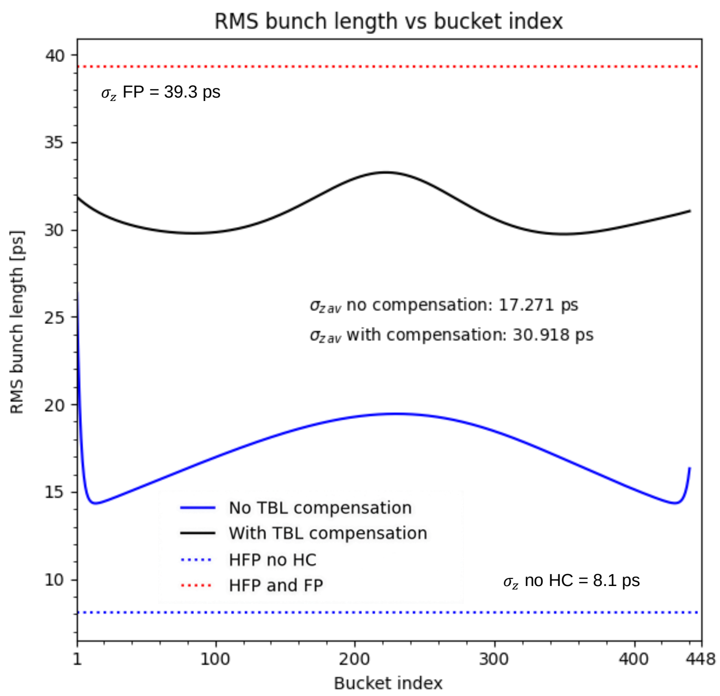
TBL COMPENSATION - ALBA II CASE

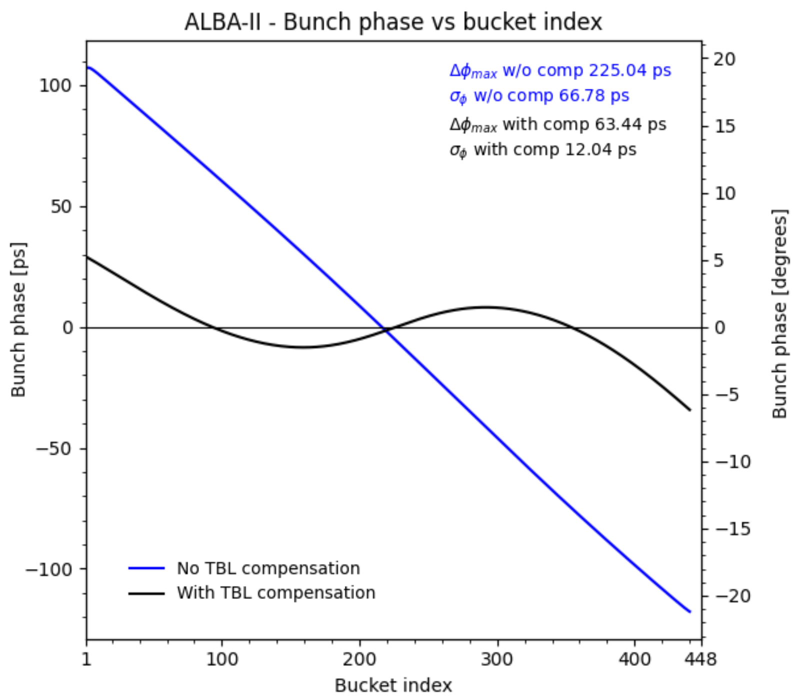
- Even if **just a 2% of gap** has a **heavy impact** on the average bunch length, further increasing it does not seem to worsen it much
- For **gaps < 2%,** compensations higher than 97% should be **easily achieved**
- **Tracking** simulations for the **compensation** case are in progress



TBL COMPENSATION - ALBA II CASE

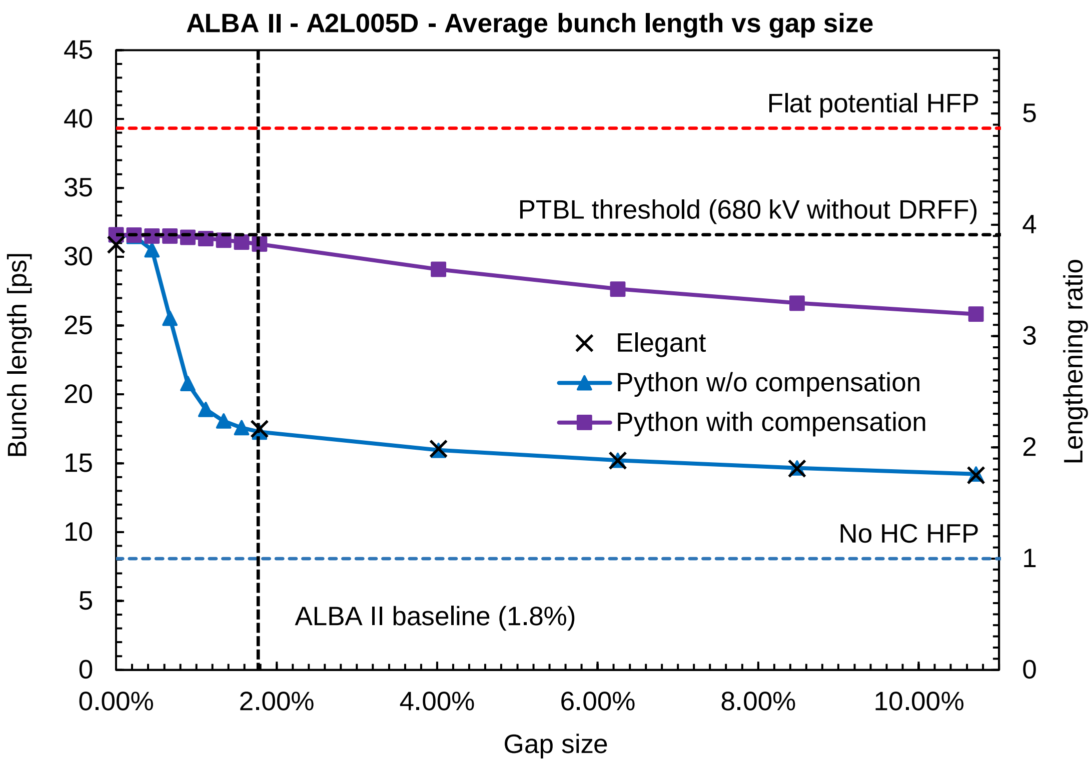
- In the ALBA II baseline scenario (with only a 1.8% gap), correcting only the 1st revolution harmonic would yield a **very high compensation efficiency**, with an average bunch length of 30.92 ps, around 98% of the no-gap case, 31.6 ps.





TBL COMPENSATION - ALBA II CASE

- The bunch **form factor and bunch phase** have been included in the TBL calculation. Convergence is achieved after approximately 10-15 iterations
- **Tracking simulations** have been performed with elegant to cross-check the semi-analytical results, showing **good agreement** between both approaches within the linear region



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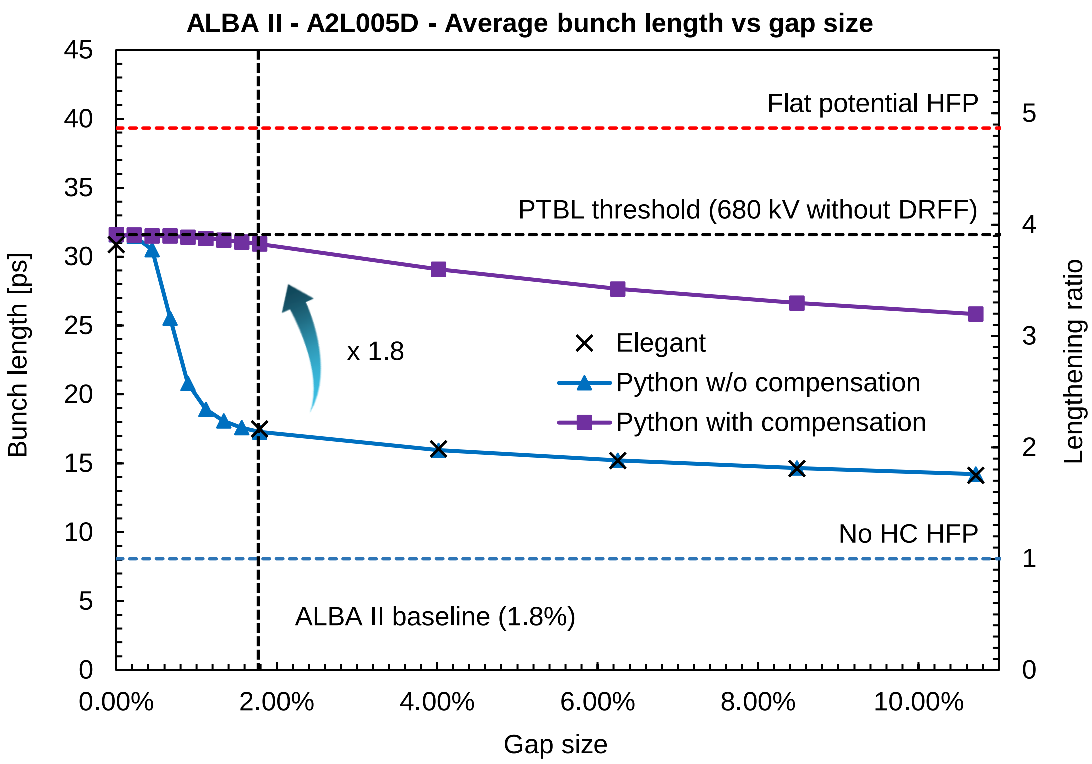
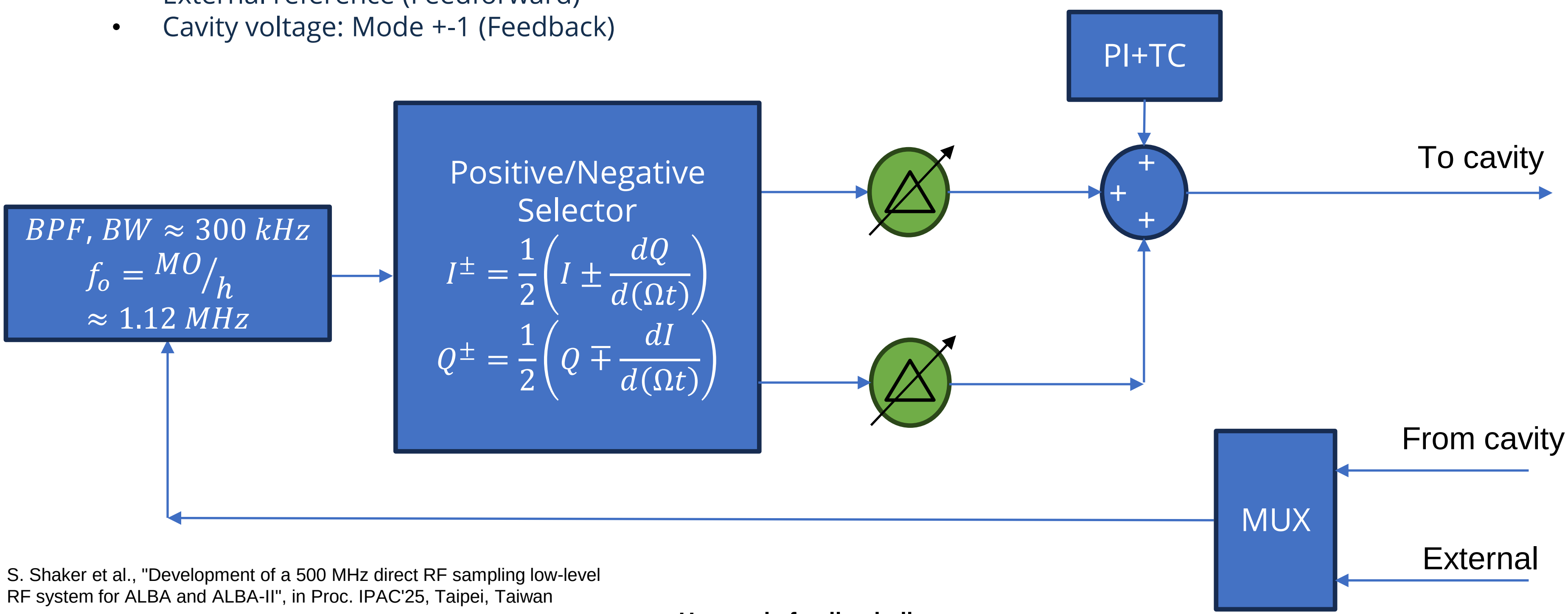
- **Tracking** simulations for the **compensation** case are in progress



Implementation on the LLRF system

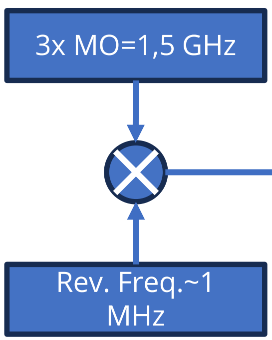
- Implemented a new control module includes IIR bandpass-filter and positive/negative frequency separator modules.
- Feedforward/feedback drive allows to send revolution harmonic content to cavities.
- Source can be chosen between:
  - External reference (Feedforward)
  - Cavity voltage: Mode +-1 (Feedback)



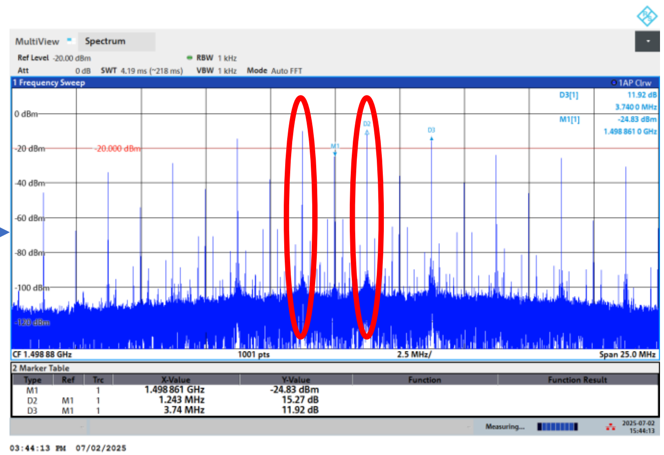
S. Shaker et al., "Development of a 500 MHz direct RF sampling low-level RF system for ALBA and ALBA-II", in Proc. IPAC'25, Taipei, Taiwan

Harmonic feedback diagram

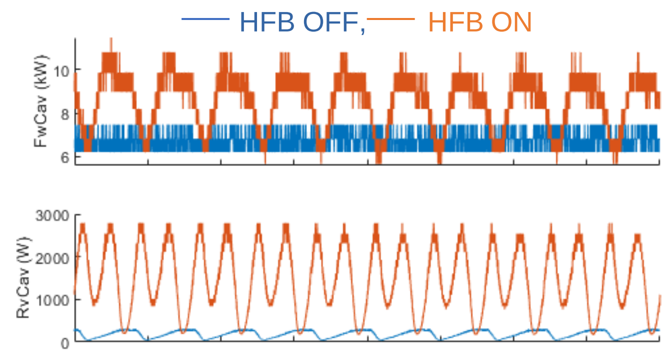
TBL Compensation: Setup



External reference experimental setup



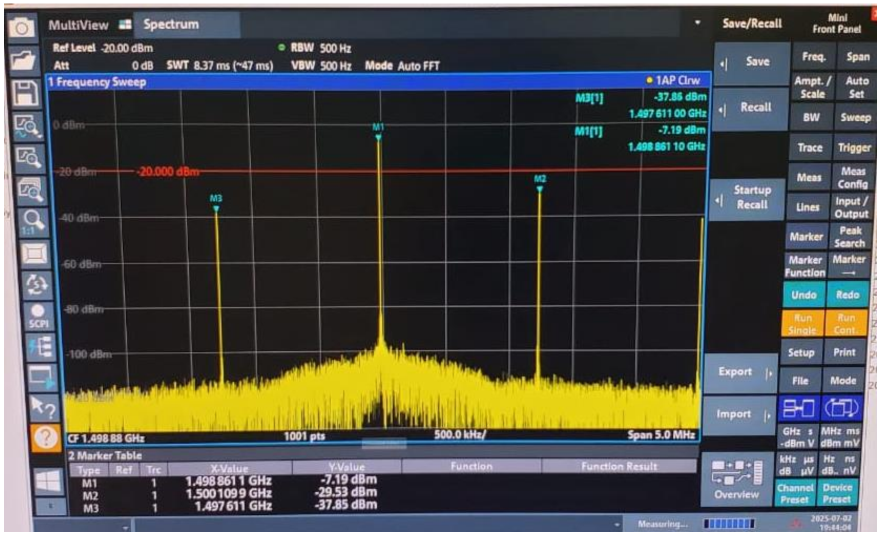
External reference harmonic content



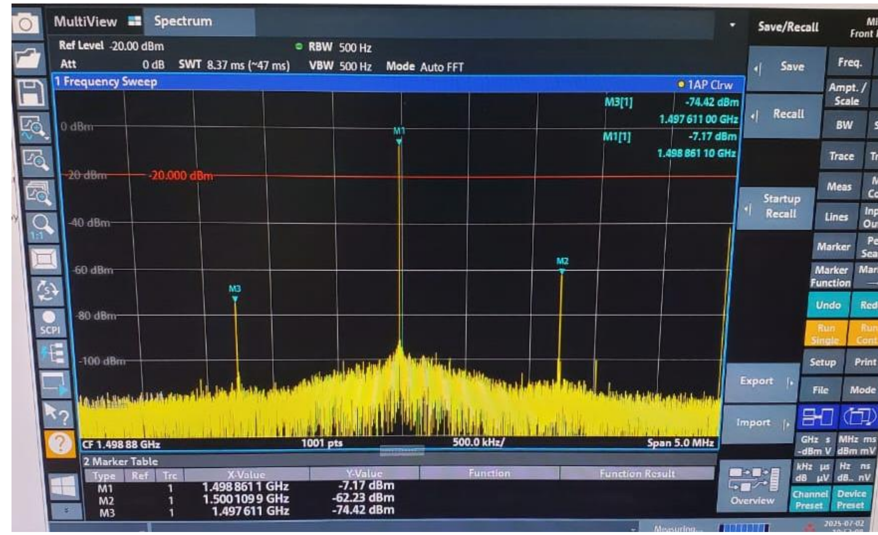
Forward and reflected power with and w/o compensation measurements

- Compensation applied during 3HC commissioning in BESSY II.
  - Current: 300 mA, Main RF Voltage: 0.7 MV (2 cavities parked, 2 with detuning -25 deg.), Landau cavities: parked, **Fill pattern: 25% gap**, 3HC: 130 kV (detuning 0 deg).
- External reference built with analogue mixer and filtered using digital harmonic resonant feedback.

TBL Compensation – Harmonic Reduction



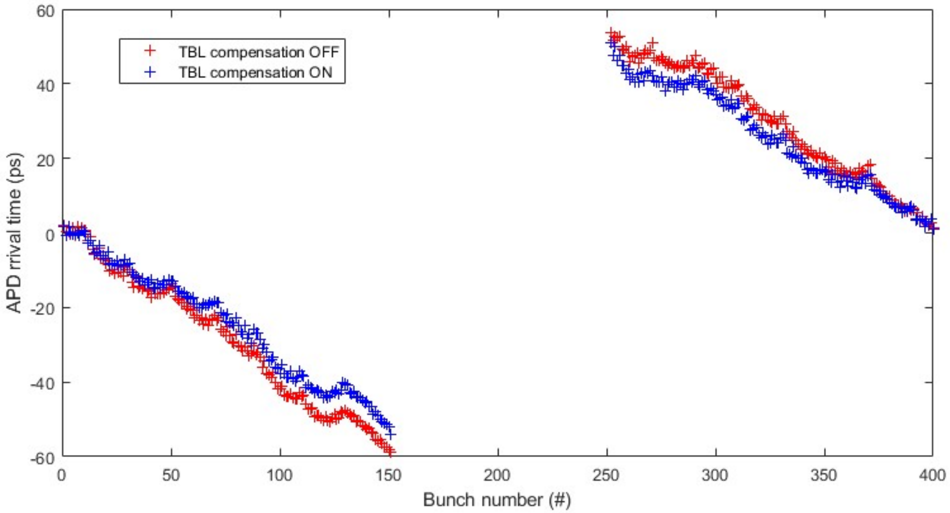
Cavity harmonic content w/o compensation



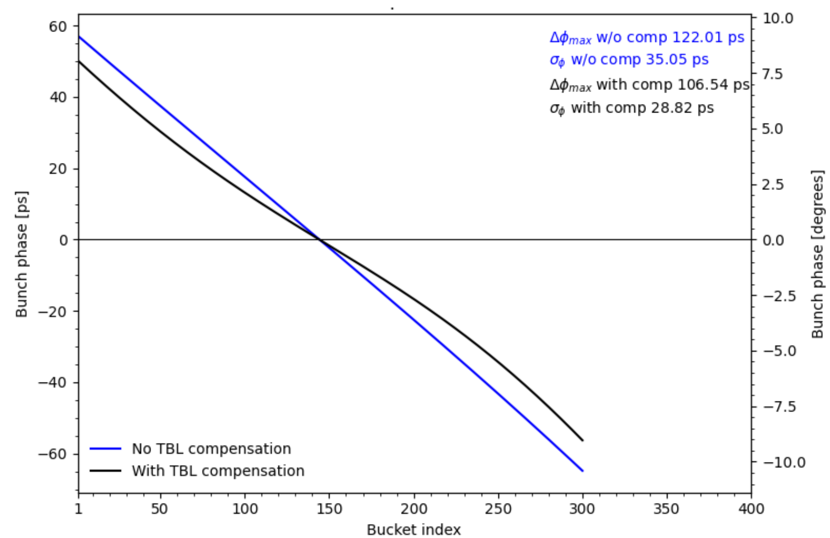
Cavity harmonic content with compensation

- Compensation applied during 3HC commissioning in BESSY II.
  - Current: 300 mA, Main RF Voltage: 0.7 MV (2 cavities parked, 2 with detuning -25 deg.), Landau cavities: parked, Fill pattern: 25% gap, 3HC: 130 kV (detuning 0 deg).
- Harmonic content of the cavity **is reduced by ~ -30 dB**.

TBL Compensation : Result



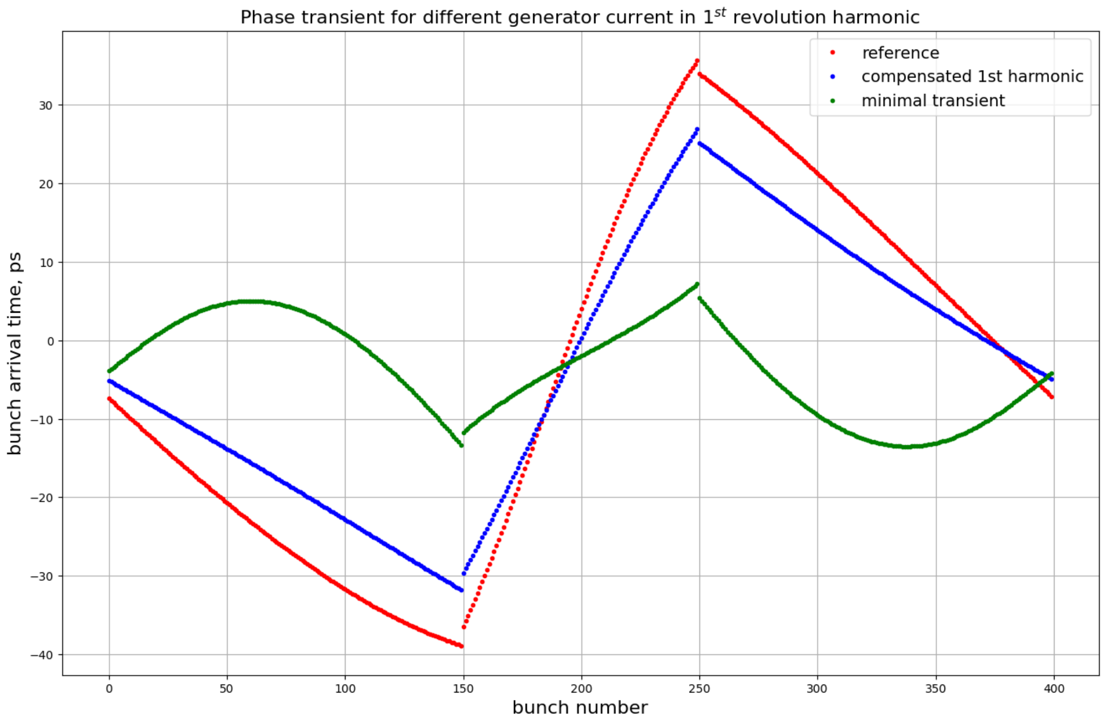
Avalanche Photo Diode arrival time with and w/o compensation measurements



Bunch phase arrival time with and w/o compensation simulation

- Compensation applied during 3HC commissioning in BESSY II.
  - Current: 300 mA, Main RF Voltage: 0.7 MV (2 cavities parked, 2 with detuning -25 deg.), Landau cavities: parked, Fill pattern: 25% gap, 3HC: 130 kV (detuning 0 deg).
- TBL compensated from 114 ps to 102 ps: **-10,5 %.**

TBL Compensation : Analysis

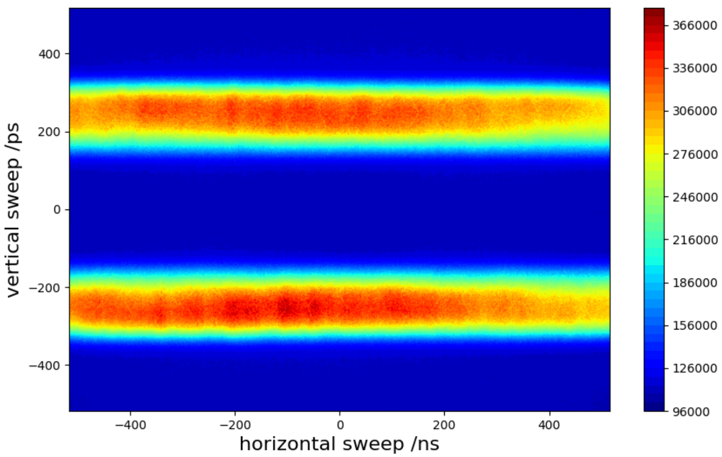


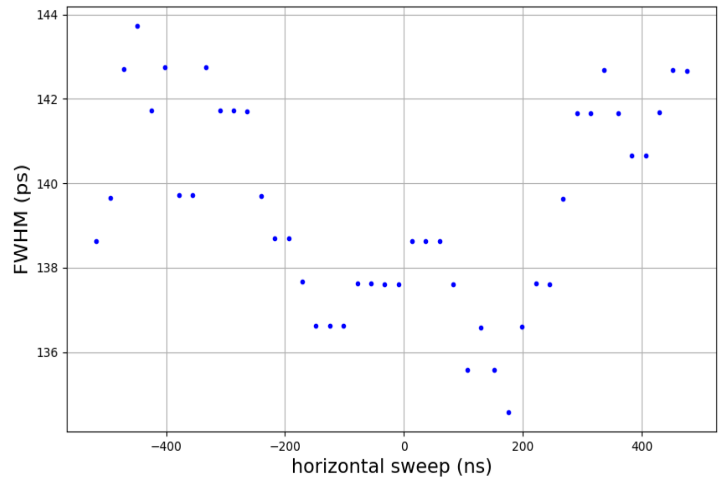
ALBA 3hc	Reference	Full compensation	Minimal phase transient
Generator current on 1st rev. harmonic, (A)	0	0.0702+0.0039j	0.250-0.034j
Phase transient (max-min, ps)	72.89	56.99	18.97

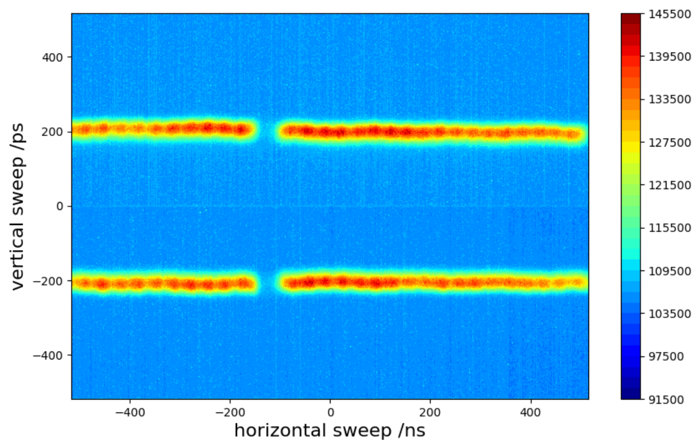
- model reproduces the numbers for reference case (blue) and for the case of compensated 1st harmonic (red)
- Transient for the case of compensated 1st harmonic is achieved at generator current I_{gen}=-(-0.070-0.0039j)
- minimal phase transient amplitude is predicted for I_{gen}=-(-0.250+0.034j) (green)
- This last case was not observed

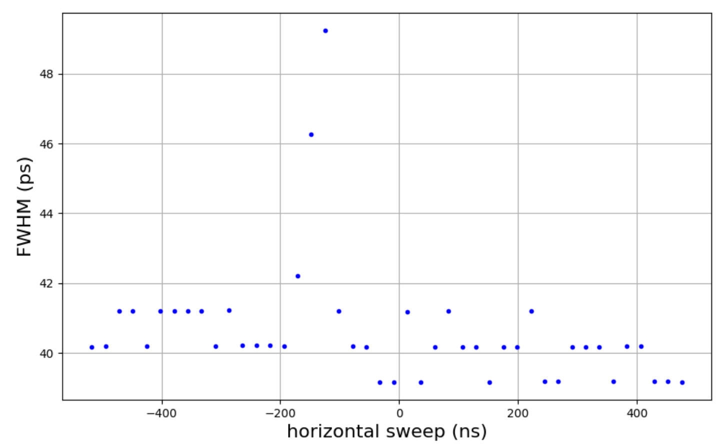
Flat Potential Operation

300mA homogeneous filling pattern beam
close to flat longitudinal potential at BESSY II







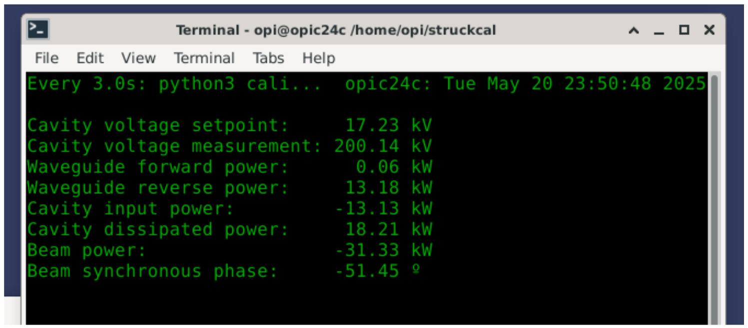


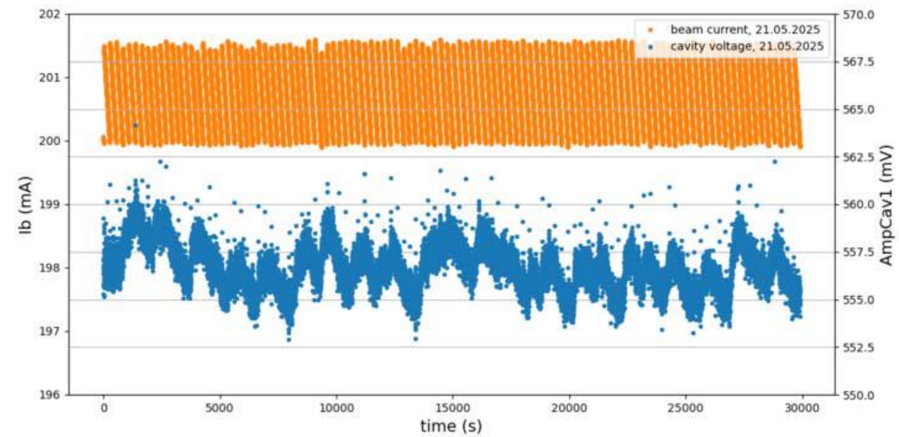
30-bunchs gap, 1.0MV main RF
Harmonic cavities parked

Flat Potential Operation - Steps

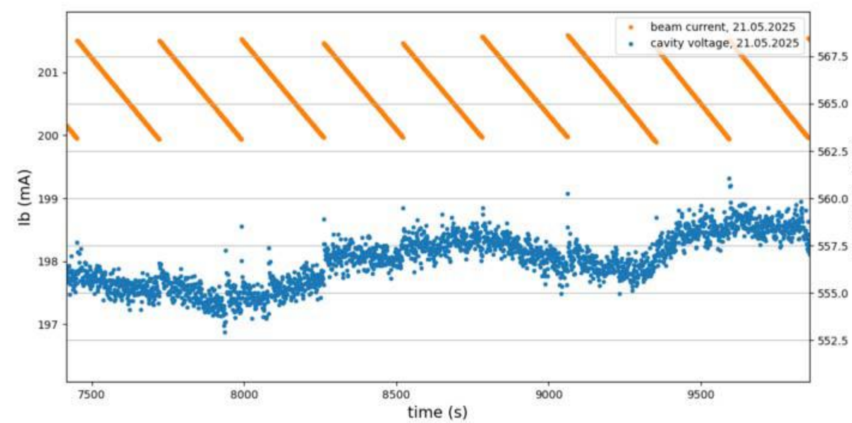
	Main RF	Passive 3hc	Active 3hc	Fill pattern	Current achieved	transient / bunch length (FWHM)	Life time	Comments
1	1400kV (4x350kV)	4x3kW (=270kV), lengthening (l)	120kV	Gap 100 bunches	300mA	250ps/ ?	5.9H	We already new it is a stable state, however lifetime improvement is small due to the transient
2	1400kV	4x3kW, (l)	70kV, 120kV	Homogeneous	250mA	~15ps/ ?	11.9H	4 tries with beam losses at current from 254mA to 267mA Increasing active 3hc amplitude does not make it better…
3	1400kV	Park-lengthening (+0.5 F_rev)	70kV, 120kV	Homogeneous	242mA, 211mA			Reduced threshold advises it could be mode 1 coupled bunch instability. To stabilize it additional impedance at -1 revolution harmonic would help -> park something there!
4	1400kV	4x3kW, (l)	parked (-0.5 F_rev)	Homogeneous	300mA		8.9H	It works! Stable for 40 min during lunch break. -> Reduce main RF.
5	950kV	4x3kW, (l)	parked (-0.5 F_rev)	Homogeneous	300mA		12.5H	Unstable at lower main RF amplitudes, but it is a different kind of instability, the beam does not get lost. -> Park a passive 3hc at ~-0.6 F_rev and activate ALBA 3hc.
6	1400kV	3x3kW, (l) LC3 at ~-0.6 F_rev	100kV	Homogeneous	300mA		9.44H	Stable! -> Reduce main RF.
7	1040kV	3x3kW, (l) LC3 at ~-0.6 F_rev	115kV	Homogeneous	300mA	~9ps/ 140ps	15.6H	Stable! Close to quartic potential!

Passive Loop Operation – 200kV & 210kV

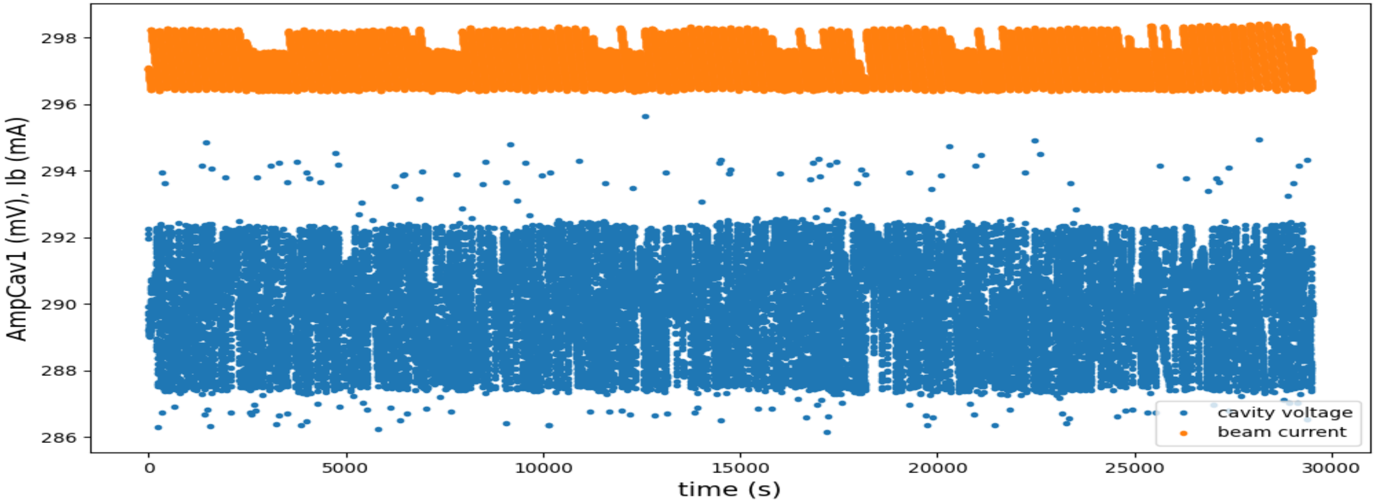


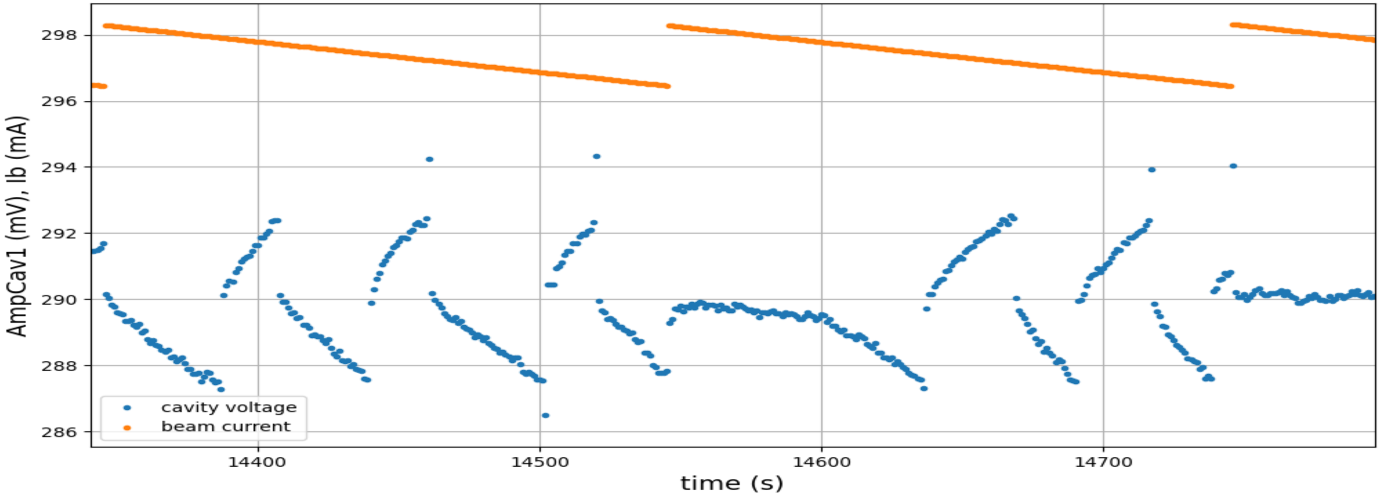


For the stability test over night:
- switch OFF 3hc SSA
- set water flow of the RF load after circulator to ~27 (l/min)
- set slow interlock reflected power level to 20kW (73.0 dBm)
- inject 200mA and go to passive loop on the shortening side at **200kV** (~18.3 kW cavity dissipated power)
- Long stability test for this setup - overnight.
- Maximum stable **210kV** was achieved.

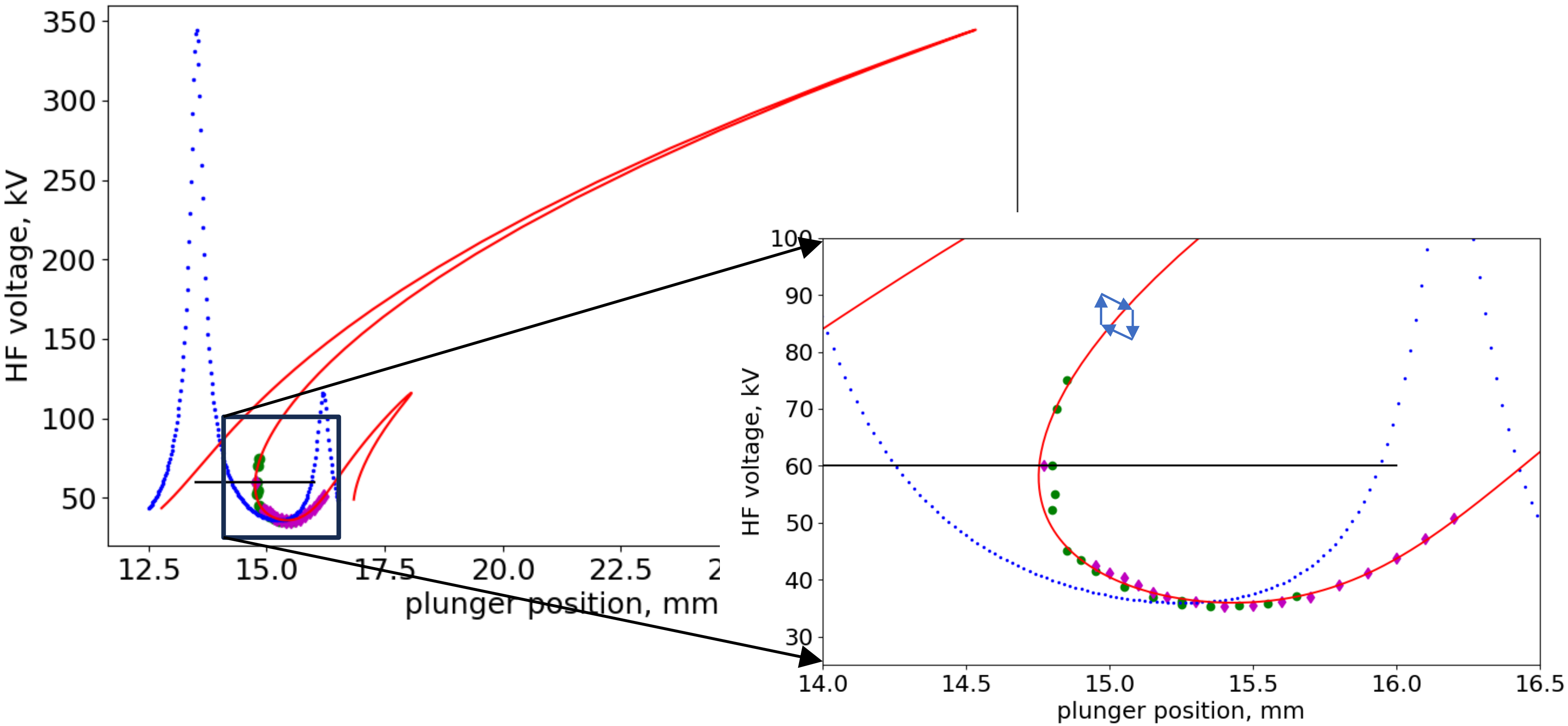


Passive Loop Operation - 100 kV





Passive Loop Operation – Thermal instability



- Cavities are on thermally unstable arm in lengthening
- Picture for a passive 3hc (BESSY-II Landau cavity)
- Blue arrows – LLRF passive loop operation

ALBA

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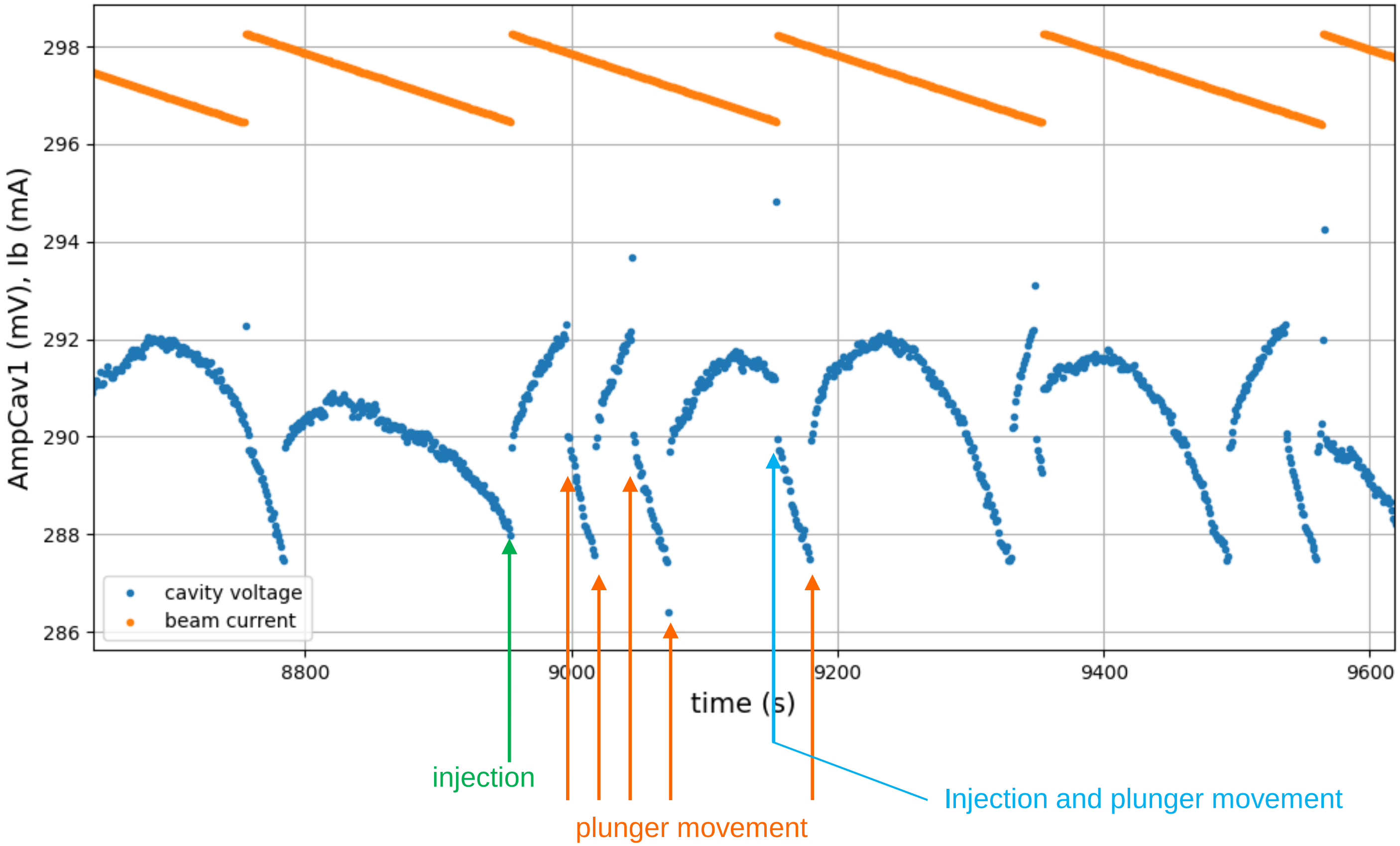
Passive Loop Operation

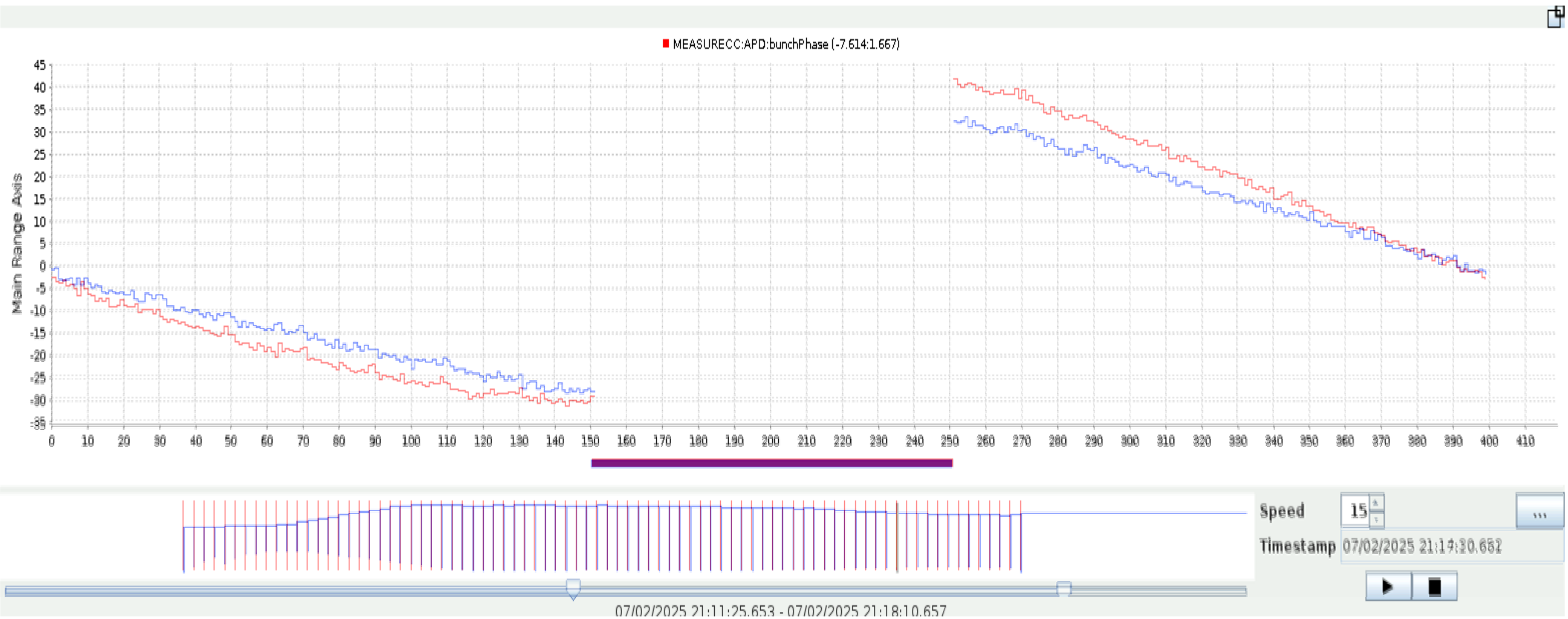


- Outliers by plunger movement or injection
- Both by plunger movement up and down

Test at BESSY-II

- Machine state: current 170mA, amplitude main RF - 1.4MV, Landau cavities – lengthening, fill pattern - 25% gap, ALBA 3hc – "parked" close to +1 rev. harmonic (plunger pos. 4.39).
- Two transients recorded on 02.07.2025 overlayed: timestamps 21:14:25 (red, without compensation) and 21:17:10 (blue, with compensation). Transient reduction according to E_log from 73ps to 57ps, or about 20%.

- The revolution signal mixed with the master Oscillator signal and fed to the LLRF system for the feed-forward system



Test at BESSY-II

- Machine state: current 300mA, main RF - 0.7MV (2 cavities parked, 2 with detuning -25 deg.), Landau cavities – parked, fill pattern - 25% gap, ALBA 3hc – at 130 kV, 0 deg.
- Two transients recorded on 02.07.2025 overlayed: timestamps 22:32:00 (red, without compensation) and 22:36:30 (blue, with compensation). Transient reduction according to E_log from 114ps to 102ps, or about 10%.