Tests with beam at BESSY-II of the ALBA 3rd harmonic active RF cavity

Ignasi Bellafont, on behalf of the 3HC collaboration - ALBA, HZB, DESY

14/02/2024, 9th Low Emittance Rings Workshop, CERN

OUTLINE

1. Introduction

- Motivation of the harmonic cavity development
- General features of ALBA’s 3^{rd} harmonic cavity

2. Tests at BESSY-II

- HOM damping tests
- Voltage stability
- Bunch lengthening performance
- Constant power phase loop

3. Conclusions

1. INTRODUCTION

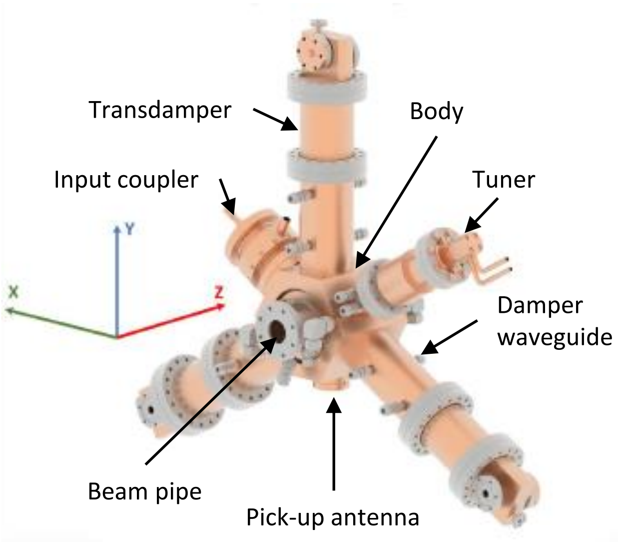
MOTIVATION

ALBA-II storage ring v 2023.8	
Beam energy	3 GeV
Circumference	268.80 m
Main RF frequency	500 MHz
Beam current	300 mA
Momentum compaction factor	$9.6 \cdot 10^{-5}$
Equilibrium emittance	186 pm·rad
Energy loss with IDs	1.13 MeV
Natural RMS bunch duration	6.97 ps
Natural Touschek lifetime FC*	5.5 h

** With full coupling. Otherwise, the Touschek lifetime is around 0.8 h*

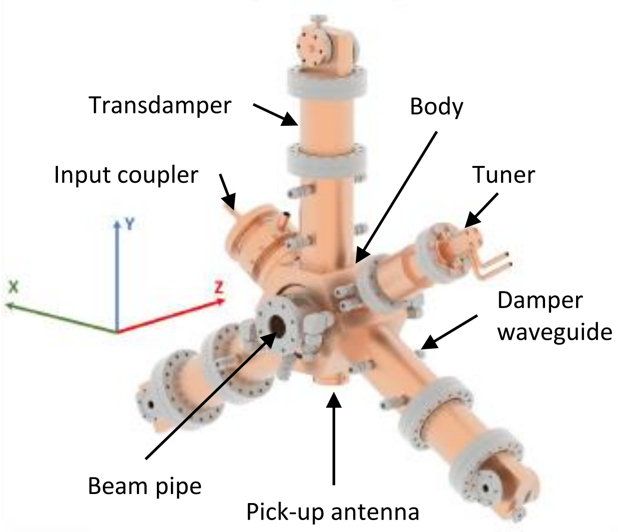
- ALBA-II, the 4th generation upgrade of ALBA, needs a double RF system to ensure a reasonable beam lifetime (> 10 h)
- For 2.4 MV of main RF voltage, at 500 MHz, we need around 685 kV of harmonic one, at 1500 MHz
- To achieve that, it was proposed to incorporate an active normal conducting, third harmonic system
- ALBA has developed the cavity, and to test it, a collaboration between three institutions (ALBA, HZB and DESY) was formed

ALBA's 3rd HARMONIC CAVITY



- The 1500 MHz cavity is a down-scaled version of the 500 MHz HOM Damped EU cavity
- The main difference is that the damping mechanism of the HOMs at the end of the dampers it is a broad band antenna which couples the power to an external load
- A prototype was manufactured in 2021 by ALBA and tested at BESSY-II during 2022-2023

ALBA's 3^{rd} HARMONIC CAVITY



Parameter	Value
Natural resonance frequency	1498.96 MHz
Shunt impedance	1.1 MΩ
Unloaded quality factor	13000
Tuning range	12.4 MHz
V_c max	200 kV
P_g max	25 kW
Cavity type	NC active

- The bead pull tests in the prototype confirmed the design shunt impedance and quality factor ratio. Beam loading tests were also performed to confirm the shunt impedance
- More information about the cavity can be found in *Third harmonic normal conducting active cavity collaboration between HZB, DESY, and ALBA, IPAC 2022*

ALBA's 3rd HARMONIC CAVITY

Main RF cavity (DAMPY)
600 kV max - 500 MHz

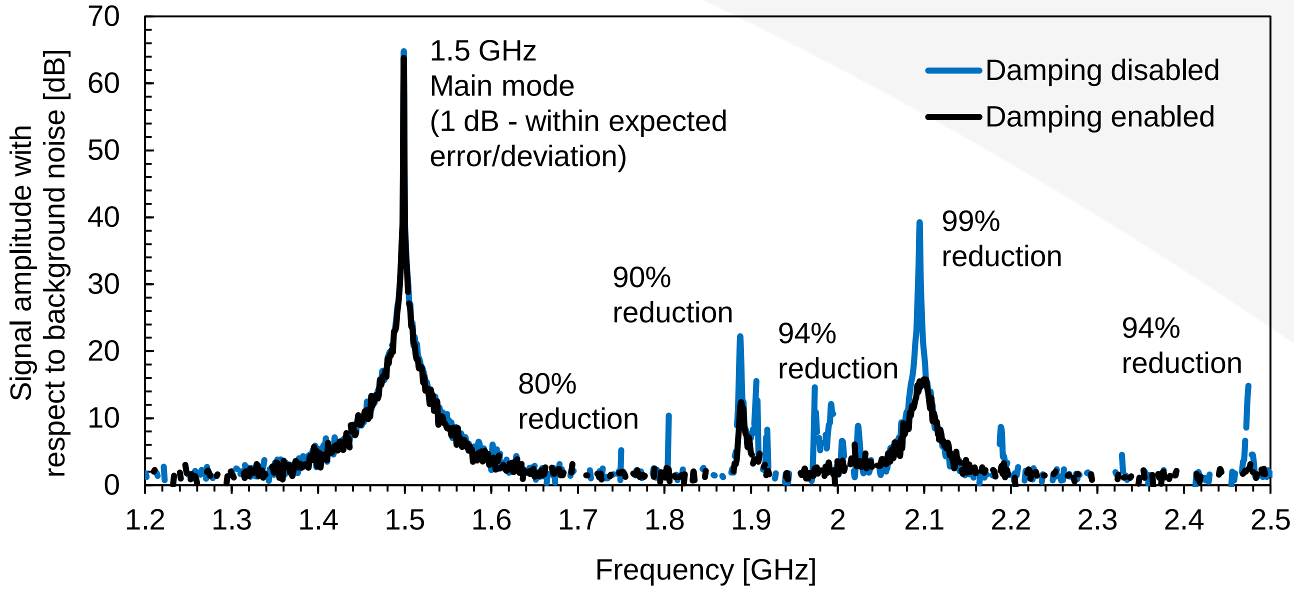
3rd harmonic RF cavity
200 kV max - 1500 MHz
3 times smaller
3 times less voltage
3 times higher frequency

WHY AN ACTIVE CAVITY ?

- It enables a complete control of the average voltage amplitude and phase for any current value
- It offers a substantially higher voltage amplitude and phase stability, so it is easy to work closer to an optimal setting, and thus obtain a higher performance, before triggering beam instabilities
- It allows to mitigate the bunch lengthening performance decrement ascribed to the transient beam loading (TBL) by means of a dedicated voltage compensation signal
- It enables the possibility of implementing a Direct RF Feedback system (DRFF). With the DRFF it is possible to achieve lower main voltages before instabilities arise, raising the harmonic voltage threshold of the Periodic Transient Beam Loading instability (PTBL), the main factor limiting our harmonic system lengthening performance
- Last but not least, it allows us to mitigate the energy losses of the harmonic system after a main cavity interlock, helping our Trip Compensation System (TCS) to make the beam survive after the huge longitudinal kick that the loss of a cavity entails

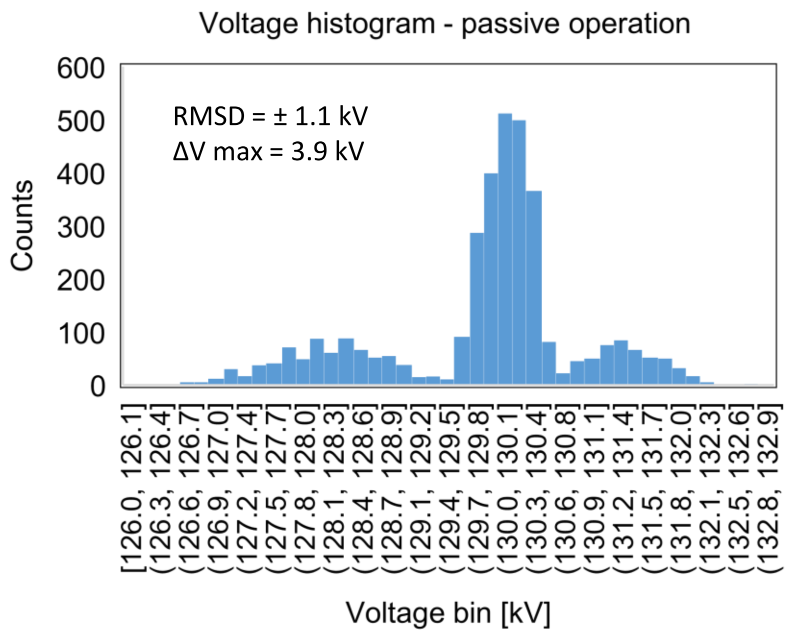
2. TESTS AT BESSY-II

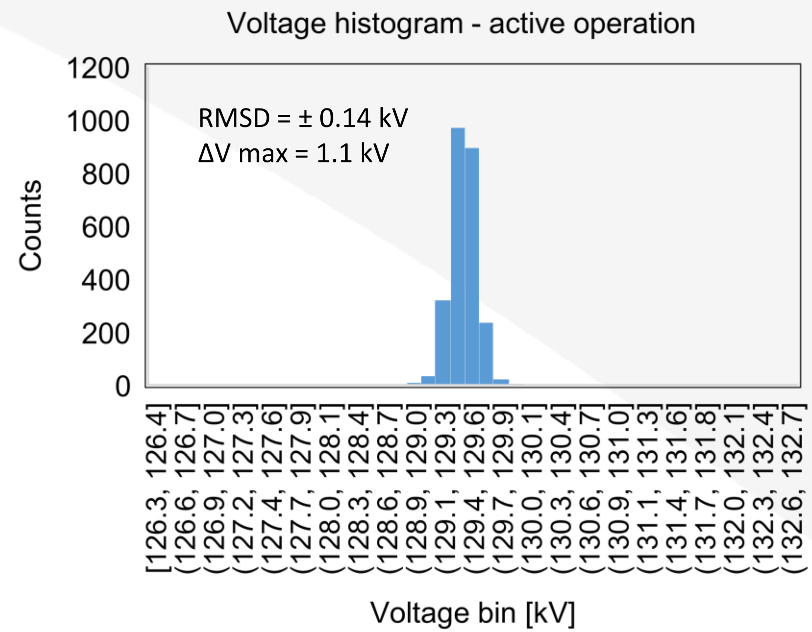
HOM DAMPING



- By connecting/disconnecting the 50 Ω load at the end of the dampers, we can enable/disable the dampening effect of the cavity
- A reduction of 80-99% of the R_s associated to the higher order modes (HOMs) was measured while using the beam as a power source
- Simulations predict well the attenuation of HOM before 3 GHz. After this frequency, they are still attenuated but to a lesser degree

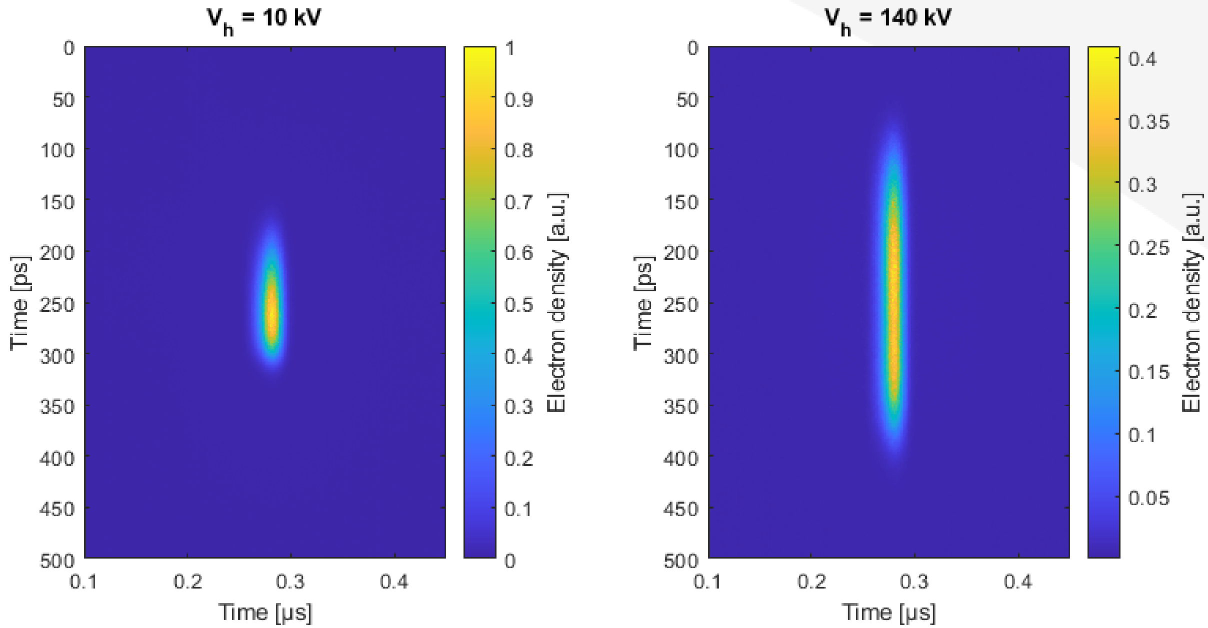
VOLTAGE STABILITY





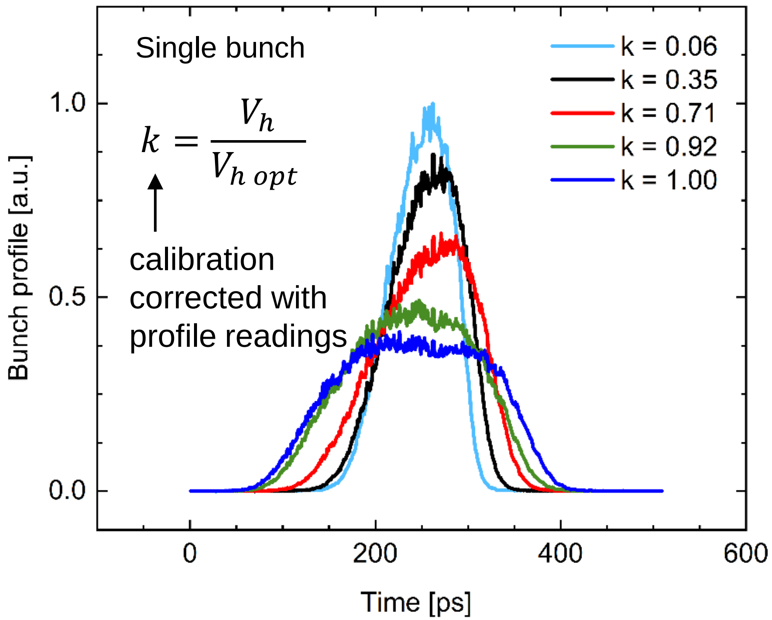
- The voltage stability over time (amplitude and phase) with beam was assessed, both in passive and active operation modes
- The maximum voltage deviation in active mode is 1.1 kV, 3.5 smaller than in passive mode
- This means that working in active mode, we can work around 11 kV closer to the threshold voltage setting, increasing around a 10% the lengthening performance of the ideal studied case

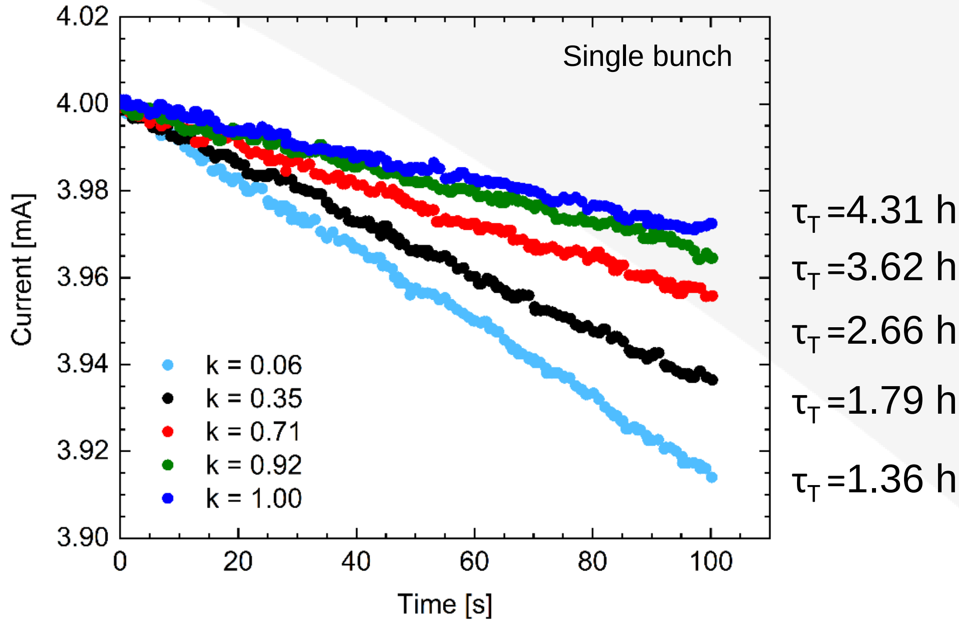
BUNCH LENGTHENING PERFORMANCE



- The bunch lengthening capabilities of the 3HC were tested for nominal current values (300 mA) and quartic/flat potential settings
- In single bunch mode, bunch lengthening and lifetime increase values higher than 3 were obtained, in line with the optimal values that the theory predicts

BUNCH LENGTHENING PERFORMANCE





- The lifetime increase capabilities showed good results, in line with the theoretical values. Bunch shortening capabilities were also tested with identically successful results
- Tests with homogeneous filling pattern, at flat potential settings and low current, < 60 mA, were also successful. At higher current values, > 60 mA, beam instabilities started to appear, due, in part, to the fact that we were operating a very low fundamental voltage, < 500 kV

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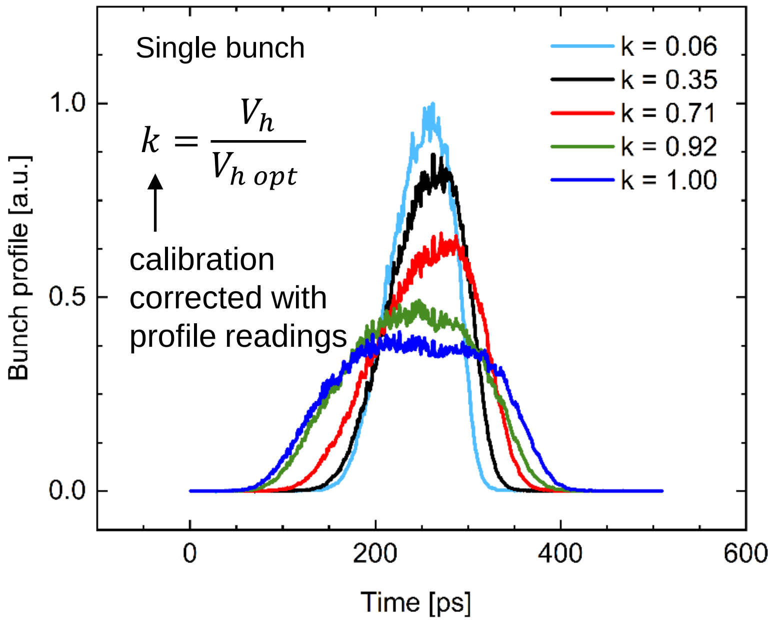

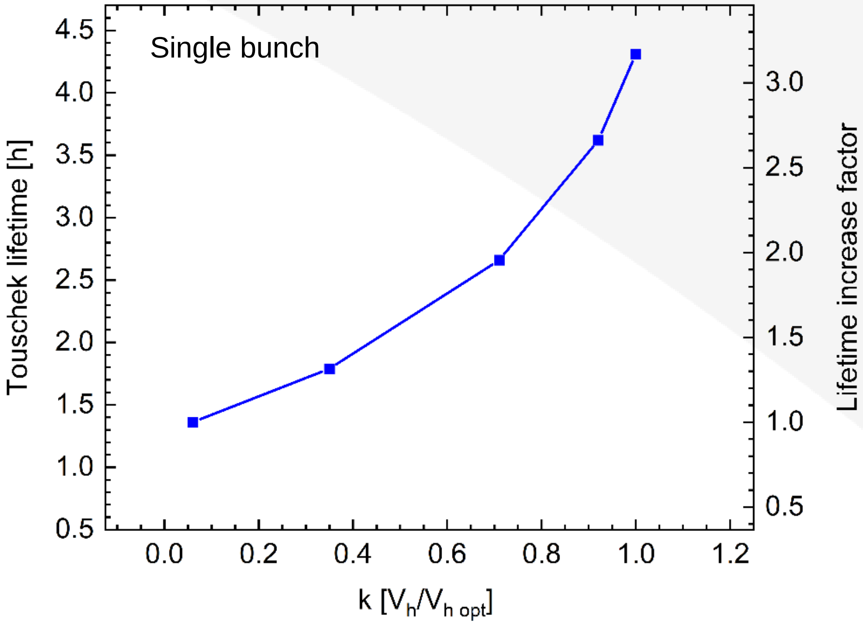

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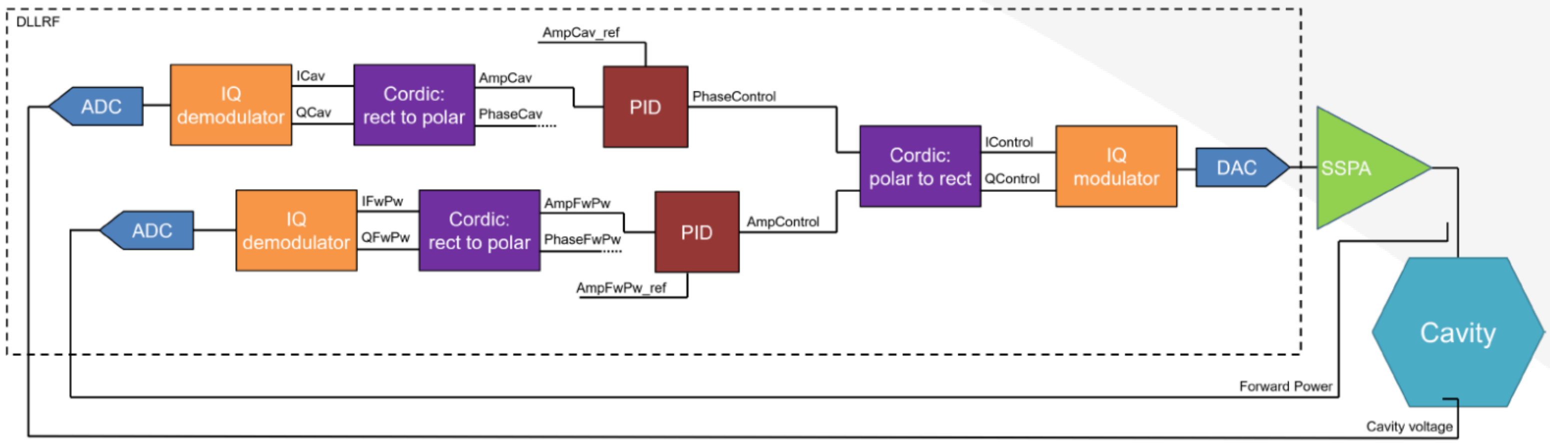
BUNCH LENGTHENING PERFORMANCE

	Max current	Main voltage	Harmonic voltage	k
	60 mA	460 kV	130 kV	1.0
Nominal current →	300 mA	615 kV	130 kV	0.75

Summary of homogeneous filling pattern tests

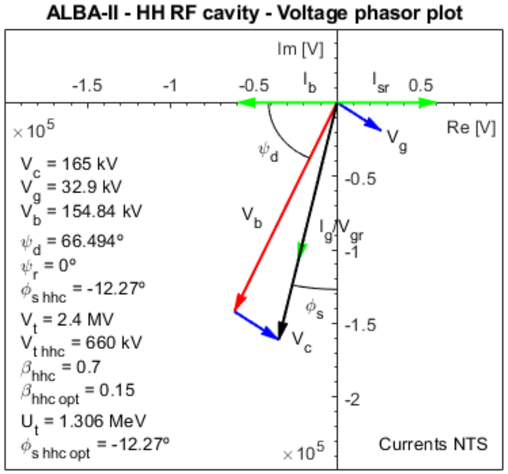
- Currently, at nominal current values, and with homogeneous filling pattern, we can only achieve around a 75% of the optimal harmonic voltage before beam instabilities appear
- The nature of the instabilities which forbid us to reach flat potential settings (k=1) with nominal beam current (300 mA) and homogeneous filling pattern are still under study. That being said, finding instabilities near flat potential conditions and high beam current values was expected, as found both experimentally and theoretically by other studies in the literature with similar R/Q values
- More information about the commissioning will be found in *Active Harmonic EU cavity: commissioning and operation with beam (to be published)*

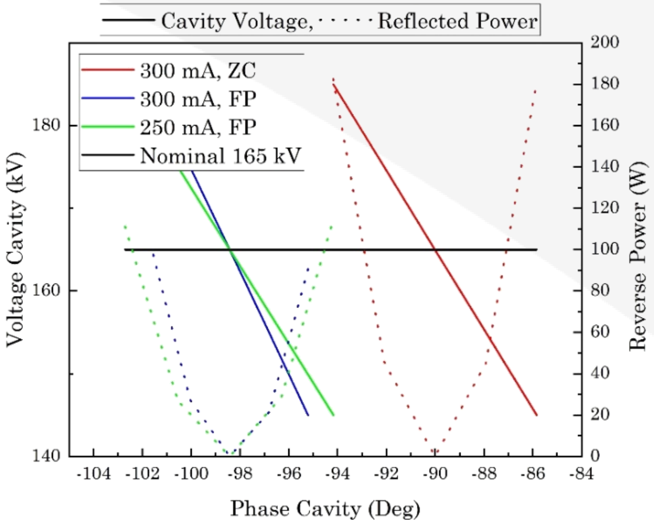
CONSTANT POWER PHASE LOOP



- In order to increase the stability of the system and simplify the phase adjustment, we have tested a constant power & phase loop, instead of the classic amplitude & phase loop
- The cavity phase is determined by the generator power setting, kept constant by the PID. The voltage amplitude, another setting, is determined by the generator phase, controlled by another PID

CONSTANT POWER PHASE LOOP





- For nominal voltage amplitude and phase settings, the 3HC will work in semi-passive mode, with its voltage mainly determined by the beam loading, not by the RF power generator
- When the beam phase changes, V_b rotates. This loop keeps the length of V_g constant and only needs a rotation to recover the V_c setting. This simpler loop has allowed us to simplify the cavity commissioning
- Further information in *DLLRF for the active harmonic RF system of ALBA-II, IPAC 2023*

3. CONCLUSIONS

CONCLUSIONS

- A prototype of the ALBA's third harmonic active RF cavity (3HC) has been tested with beam at BESSY-II storage ring. The design parameters, HOM damping capabilities, voltage stability and bunch lengthening performance were assessed, yielding successful results

- With low beam current values, the cavity is able to easily reach flat potential conditions with very little voltage fluctuations, yielding lifetime increase factors above 3. At high beam currents and homogeneous filling pattern, beam instabilities start to appear. They are still under study

- The true endgame capabilities of the 3HC, the transient beam loading (TBL) compensation and the implementation a direct feedback system to mitigate the growth rate of the HC-related beam instabilities, are yet to be tested. They are scheduled for implementation and testing within this year

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