Digital direct RF feedback for beam loading reduction at ALBA

Pol Solans

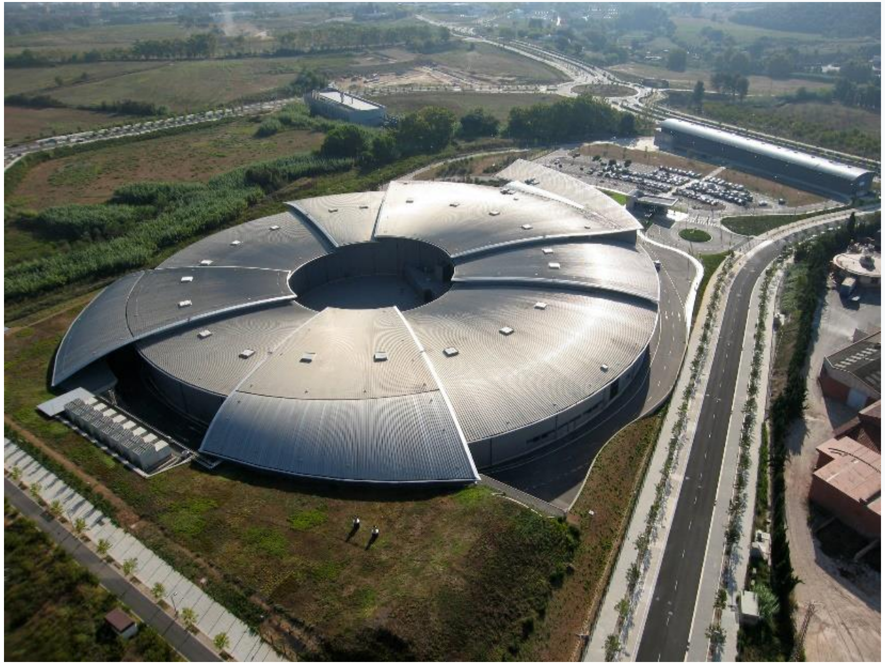
Low Level Radiofrequency Workshop 2023

Outline

- Introduction
  - ALBA
  - RF system
  - DLLRF
- Direct RF feedback
  - Implementation
  - Experimental results
    - Tune measurement
    - Longitudinal kicks
- Summary

- ALBA is a 3rd **generation synchrotron light source** located in Barcelona, Spain.
- **User operation since 2012** and currently **12 beamlines**.

Parameter	Value	Unit
Energy	3.0	GeV
Current	250	mA
Circumference	268.8	m
Momentum compaction factor	8.9E-4	-
Loses per turn	1.1	MeV
Emittance	4.5	nm·rad



- Upgrade towards 4th generation planned in 2030: **ALBA-II**

Introduction: RF system

- Storage Ring: **EU HOM damped cavity** (500 kV) fed with **IOT amplifiers** (2x80 kW).
- Booster: **5-cell Petra** type cavity and a **SSPA** (50 kW).

Parameter	Value	Unit
RF frequency	500.0	MHz
Number of cavities	6	-
Total voltage	3.0	MV
Cavity shunt impedance	3.3E6	Ohm
Unloaded quality factor	29500	-
Coupling factor	2.7	-
Beam power	275	kW

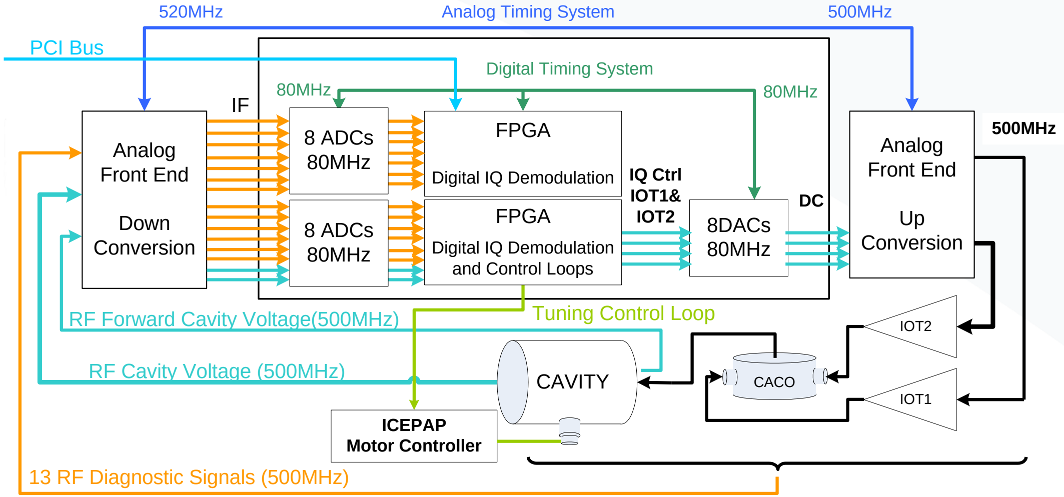
EU HOM damped cavity

IOT transmitter

BO SSPA

- ALBA DLLRF is based in the **VHS-DC digital board** from **Lyrtech**.

Digital board: VHS-ADC from Lyrtech

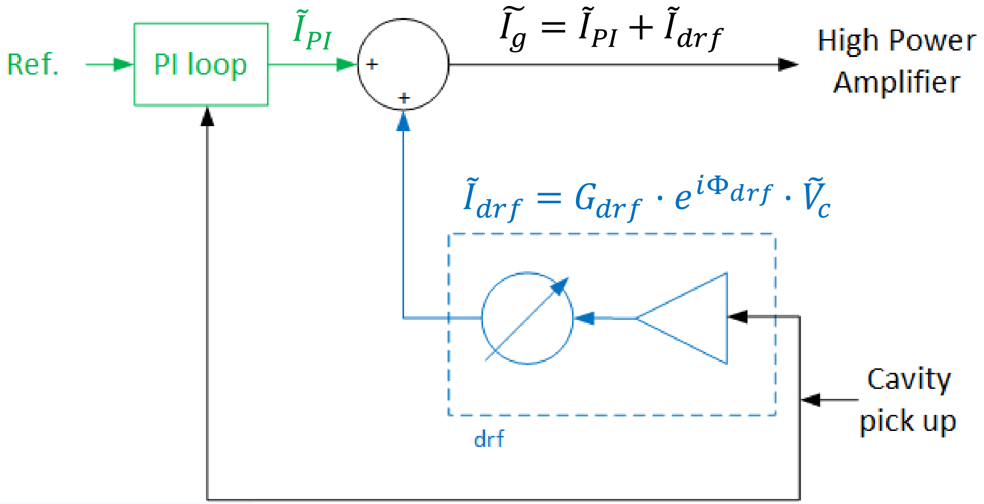


*Courtesy of Angela Salom

- In house firmware: PI and tuning loops, trip compensation, cavity autorecovery and **direct RF feedback (drf).**

Digital drf: Implementation

- Direct RF feedback (drf) virtually **reduces the impedance** of the cavity as seen by the beam.
- It is useful for zero mode **instabilities and oscillations mitigation**.



- Amplitude and phase loop
- Direct RF feedback

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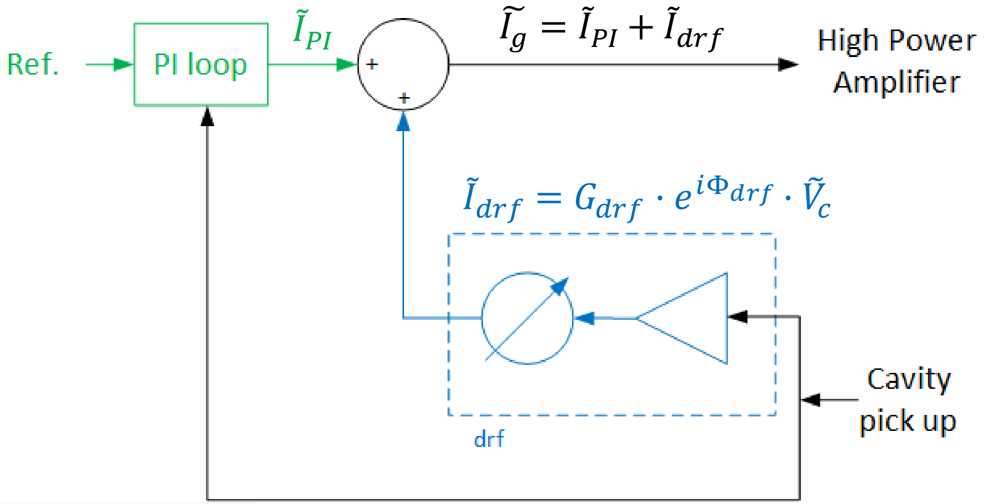

- Amplitude and phase loop
- Direct RF feedback

$$\frac{R_{SL,dr}}{R_{SL}} = \frac{1}{1 + \gamma_{dr} \cos \Psi_{dr}}$$

$$\gamma_{dr} = \frac{\alpha_{dr}}{\alpha_{dr} + 1} \qquad \tan \Psi_{dr} = \frac{\tan \Psi_d + \gamma_{dr} \sin \Phi_{drf}}{1 + \gamma_{dr} \cos \Phi_{drf}}$$

$$\alpha_{dr} = \left| \frac{I_{drf}}{I_{PI}} \right| \qquad \Phi_{dr} = angle\left(-\frac{I_{drf}}{I_g} \right)$$

Kazunori Akai, "**Stability analysis of rf accelerating mode with feedback loops under heavy beam loading in SuperKEKB", PRAB 25, 102002**

Digital drf: Implementation

- Gain (G_{dr}) and phase shift (Φ_{dr}) are **easily adjustable** to get desired γ_{dr} and Ψ_{dr}.

SETTINGS

	Write	Read Back
DRF Enable	ON	True
DRF Gain	0.4	0.40
DRF Phase	-170	-170.00 deg

DIAGNOSTICS

	I	Q	Amp	Phase
CavityReference	153.87 mV	671.90 mV	689.29	77.10
Cavity Voltage	152.93 mV	670.03 mV	687.26	77.14
Control Action	60.82 mV	266.21 mV	273.07	62.20
Direct Feedback	-61.43 mV	-271.40 mV	278.27	-118.18
PI Output	124.79 mV	538.80 mV	553.07	76.96

$$\begin{cases} \alpha_{dr} = \left|\dfrac{I_{drf}}{I_{PI}}\right| \\ \Phi_{dr} = angle\left(-\dfrac{I_{drf}}{I_g}\right) \end{cases}$$

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$$\alpha_{dr} = \left|\frac{I_{drf}}{I_{PI}}\right| = \frac{278}{553} \approx 0.5 \Rightarrow \gamma_{dr} = \frac{\alpha_{dr}}{\alpha_{dr}+1} = 1$$

$$\Phi_{dr} = angle\left(-\frac{I_{drf}}{I_g}\right) \approx 0º \Rightarrow \tan\Psi_{dr} = \frac{\tan\Psi_d + \gamma_{dr}\sin\Phi_{drf}}{1+\gamma_{dr}\cos\Phi_{drf}} = \frac{\tan\Psi_d}{2}$$

$$\frac{R_{SL,dr}}{R_{SL}} = \frac{1}{1+\gamma_{dr}\cos\Psi_{dr}}$$

- Beam loading leads to a **synchrotron frequency shift** proportional current and **cavity impedance**.

$$\frac{\Delta f_s}{f_o} = -\frac{I_b \beta Z_i^0}{V_c |\cos \Psi_s|}$$

$$\frac{\Delta f_{s,drf}}{\Delta f_{s,o}} = \Delta Z_i^0 = \frac{1}{1 + \gamma_{dr} \cos \Psi_{dr}}$$

Digital drf: Experimental results

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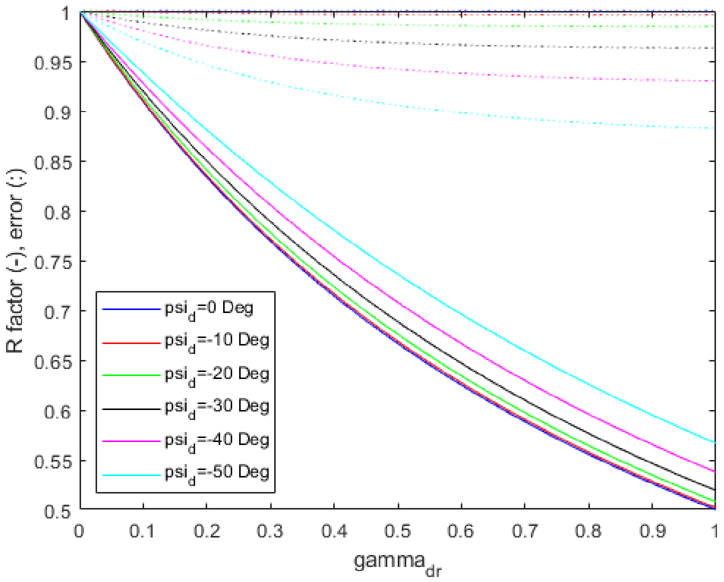
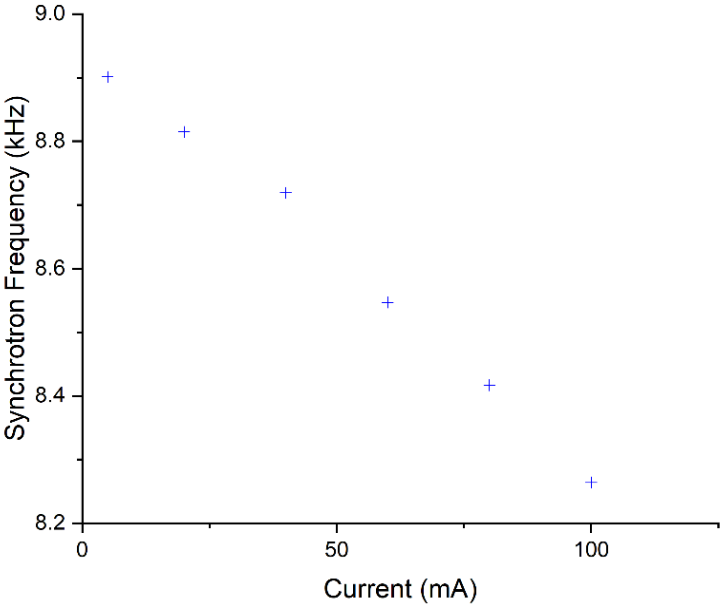


- If $\Phi_{dr} = 0º$ and $\Psi_d \approx small$ then $\gamma_{dr}\cos \Psi_{dr} \approx \gamma_{dr}$

$$\frac{\Delta f_{s,drf}}{\Delta f_{s,o}} \approx \frac{1}{1+\gamma_{dr}}$$

- Synchrotron frequency shift due to beam loading:
  - 3 MV up to 100 mA ($\Psi_d = -19º$)



Digital drf: Experimental results

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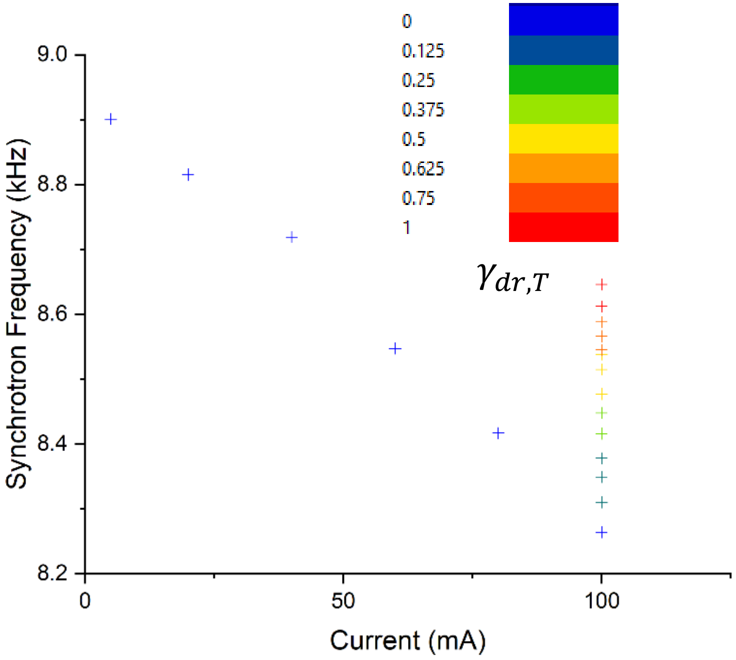

- drf adjusted in all cavities one by one.

$$\frac{\Delta f_{s,drf}}{\Delta f_{s,o}} = \frac{1}{1+\gamma_{dr,T}}$$

$$\gamma_{dr,T} = \frac{N}{\sum_{i=1}^{N} \frac{1}{1+\gamma_{dr,i}}} - 1$$

Digital drf: Experimental results

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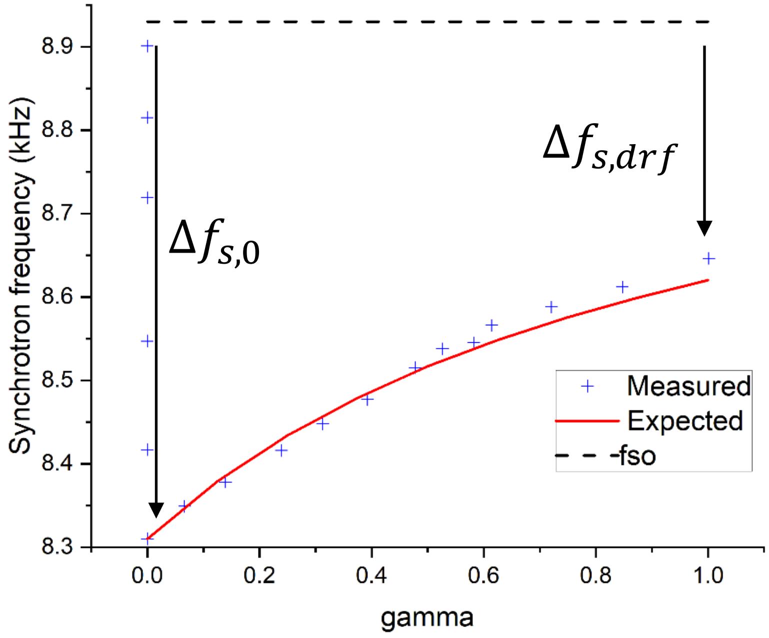

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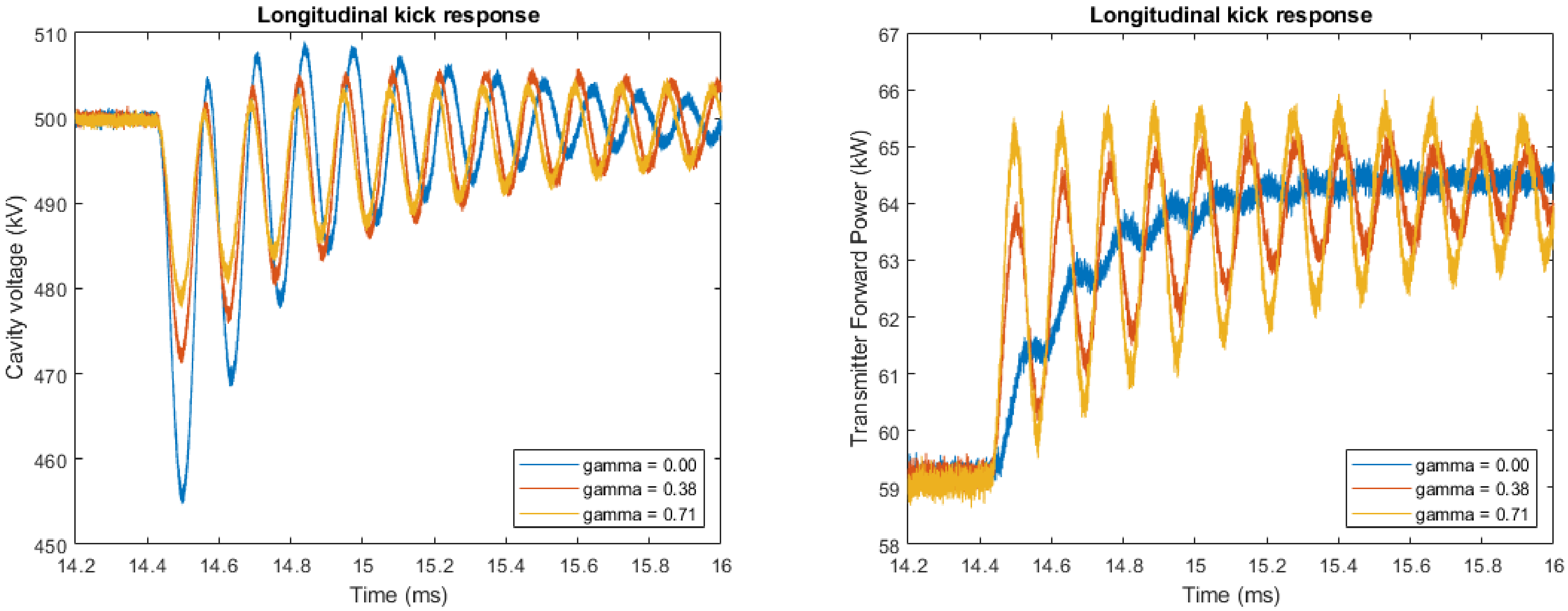
Parameter	Gamma=0	Gamma=1
Zero current freq.	8.93	8.93
Shifted frequency	8.26	8.64
Total shift	0.67	0.29
Reduction factor	-	0.43

Digital drf: Experimental results

- Synchrotron frequency shift reduction is also observed in **coherent bunch oscillations** after longitudinal kicks.



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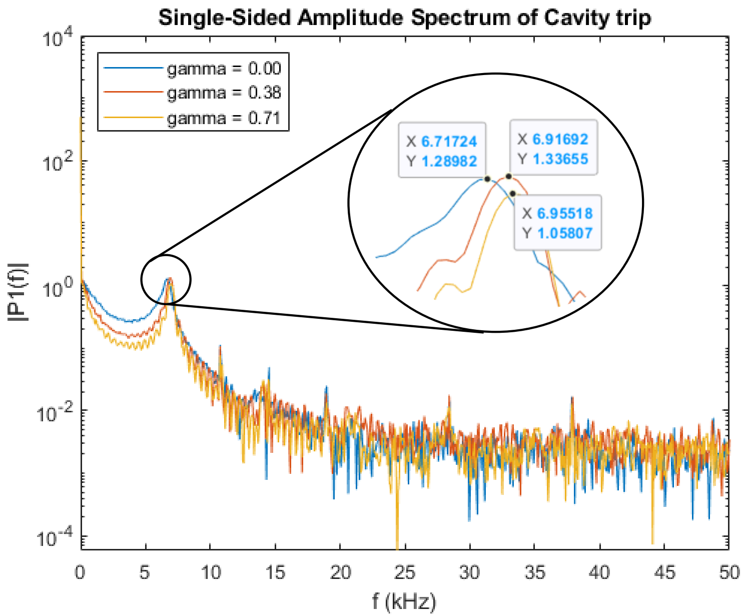

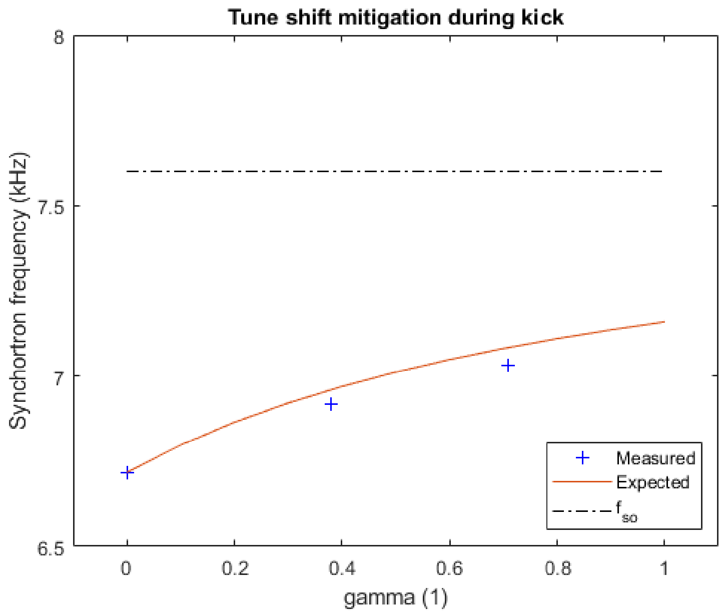

- **ALBA has implemented a digital drf** able to compensate the synchrotron frequency shift due to beam loading.
- Experimental measures and analytical model are in agreement.
- Synchrotron frequency shift mitigation is observed in steady state operation and large coherent oscillations of the beam.

Thanks for your attention