

Electromagnetic Simulations for ALBA II RF Cavities

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Abstract: This thesis presents an electromagnetic analysis of higher-order modes (HOMs) in the radiofrequency cavities for the ALBA-II upcoming upgrade. Using *CST Studio Suite*, simulations were performed on three different configurations of 1.5 GHz third-harmonic cavities (to be installed) and 500 MHz *Dampy* cavities (currently operating). A two-step approach—combining *Wakefield* and *Eigenmode Solvers*—was applied to identify resonant modes potentially affecting beam stability. Results show that all HOMs remain below impedance thresholds, except for the TM_{011} mode near 2.09 GHz, which slightly exceeds the longitudinal limit and needs further investigation.

Keywords: Radiofrequency, 3rd harmonic cavity, Beam dynamics, Shunt impedance.

SDGs: Quality education; Industry, innovation and infrastructure.

I. INTRODUCTION

ALBA is a third-generation synchrotron light source located in Cerdanyola del Vallès, Barcelona. Its radiofrequency (RF) systems accelerate electrons in both the Booster and Storage Ring, where they compensate for energy loss through synchrotron radiation.

An external high-power source (*RF Amplifiers*) generates an electric field parallel to the electrons' path inside a resonant cavity, accelerating the beam. These *RF cavities* are cylindrical conducting structures made out of copper, with axial holes for electron entry and exit. To smoothly connect cavities with different vacuum chamber diameters, a *taper*—a pipe with a gradually changing diameter—is used.

Currently, six 500 MHz RF cavities, called *Dampy* cavities, are installed in the Storage Ring. In preparation for the ALBA-II upgrade to a fourth-generation synchrotron light source, four 1.5 GHz third-harmonic RF cavities (3HC) will be added alongside them. Since the beam pipes of the cavities and the vacuum chamber have different diameters, tapers are required for all connections.

RF amplifiers supply input power to the cavity, generating an electric field parallel to the beam axis called the *fundamental mode*, with a 500 MHz frequency for the *Dampy* and 1.5 GHz for the 3HC. This mode efficiently converts power into accelerating voltage. However, accelerated electrons propagate electromagnetic fields that excite *higher-order modes* (HOMs) above the fundamental frequency. These HOMs, generated in cavities and tapers, can disturb beam stability. Since electrons travel in bunches, each bunch excites HOMs that affect subsequent ones. This might lead to instabilities that accumulate as the bunches revolve around the Storage Ring.

A computational electromagnetic study of HOMs is essential before installing harmonic cavities (see [3]). For this purpose, the finite element software CST [1] will simulate fields inside the cavities and tapers. The installation plan involves placing two consecutive harmonic cavities beside three *Dampy* cavities at two Storage Ring

locations. Accordingly, the study will sequentially analyse a single harmonic cavity, then two consecutive ones, and finally all five cavities.

Section II displays the cavity models and their key characteristics. Section III describes how HOMs are studied and presents two different computational methods. Finally, Section IV exposes the results for the different models.

II. DESIGN AND MAIN FEATURES

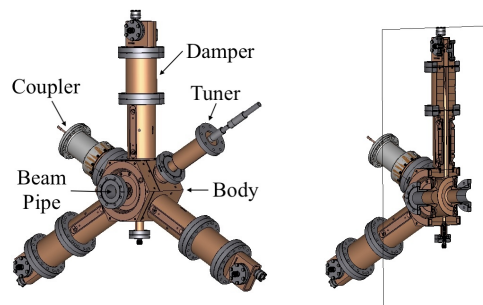


FIG. 1: Representation of a 3rd harmonic cavity (left) with a transverse cut view (right).

Figure 1 shows the model of a 3HC. The central cylindrical part, called the *body*, is where electron bunches enter and exit via the *beam pipe*. The *input coupler* feeds power into the body, while three waveguides called *dampers* attenuate higher-order modes (HOMs) by allowing only waves above a certain cutoff frequency to propagate. Finally, the *tuner* adjusts the body's fundamental frequency. This is an extremely detailed model, and it must be simplified to perform electromagnetic simulations efficiently.

Figure 2 shows the electromagnetic models of the *Dampy* and harmonic cavities. Since the fundamental frequency remains unchanged in this study, the tuner

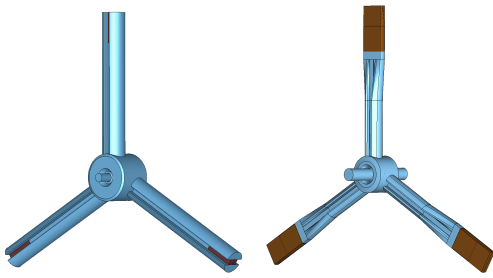


FIG. 2: Electromagnetic models of a Dampy cavity (left) and a 3rd harmonic cavity (right). Not in scale.

was removed. Similarly, the coupler was excluded, as it introduces insignificant modes that add unnecessary computational time.

III. HIGHER-ORDER MODES

A. Wake Fields

As the beam travels through an RF cavity, it induces electromagnetic fields—known as *wake fields*—which can affect beam dynamics (i.e., the previously mentioned HOMs). These fields, primarily left behind the electrons, can influence trailing particles longitudinally or transversely, potentially causing *energy loss* or *beam instabilities*. Beam dynamics can be analysed in either the time or frequency domain.

In the time domain, *wake functions* give the normalized integral of the electromagnetic force generated by a point charge, with units V/C. The *longitudinal wake function*, $w_z(x, y, \tau)$, is the integral of the longitudinal force component and quantifies the energy gained by a trailing charge due to fields excited by a leading charge. It depends on the time delay τ between them.

In the frequency domain, the *wake impedance*—with units Ω —is defined as the Fourier transform of the wake function. The *longitudinal wake impedance* is given by

$$Z_z(x, y, \omega) = \int_{-\infty}^{\infty} w_z(x, y, \tau) e^{-j\omega\tau} d\tau, \quad (1)$$

and can be expanded in a multipole series:

$$Z_z(x, y, \omega) = Z_z^0(\omega) + x \frac{\partial Z_z}{\partial x}(\omega) + y \frac{\partial Z_z}{\partial y}(\omega) + \dots \quad (2)$$

Here, $Z_z^0(\omega)$ is the *monopole* term (i.e., the longitudinal impedance along the central axis) whose real part represents energy gain. The first derivatives are the *dipole* terms (units Ω/m), interpreted as the *transverse impedance*, describing linear transverse kicks from deflecting fields. Higher-order terms are typically small corrections. As a first-order approximation, the transverse impedance can be computed as

$$Z_u(\omega) = \frac{|Z_z^{\text{offset}}(\omega) - Z_z^0(\omega)|}{u_{\text{offset}}}, \quad (3)$$

where u is the transverse direction (typically x or y), u_{offset} is a small displacement in that direction, and Z_z^{offset} is the longitudinal impedance evaluated along a path shifted u_{offset} from the centre.

B. HOMs Analysis

An RF cavity behaves as a resonant system with energy storage and dissipation, similar to a parallel RLC circuit. It supports standing electromagnetic waves at specific resonance frequencies (modes), determined by its geometry and boundary conditions. These waves can have either transverse electric or transverse magnetic fields to the electron's path—TE and TM modes, respectively. They can be classified by the number of maximums in the angular (n), radial (m), and longitudinal (l) directions: TE_{nml} and TM_{nml} . The fundamental mode is a TM mode corresponding to TM_{010} . Our main concern is the effect of HOMs on the electron beam. To characterize the perturbation, we study the *quality factor* (Q) and the *shunt impedance* (R_s) of each mode.

As in an RLC circuit, the quality factor is defined as

$$Q = \frac{\omega_n W}{P_{\text{loss}}}, \quad (4)$$

where n refers to the mode, ω_n is its angular frequency, W is the stored electromagnetic energy, and P_{loss} is the internal power loss. This dimensionless quantity measures energy storage efficiency: a high Q means the mode persists longer, potentially disturbing electrons, while a low Q indicates rapid dissipation due to low energy storage or high losses. HOMs are expected to have lower Q than the fundamental mode.

The shunt impedance of a mode—measured in Ω —is defined as

$$R_s = \frac{V_{\text{acc}}^2}{2P_{\text{loss}}}, \quad (5)$$

where V_{acc} is the accelerating voltage and P_{loss} is the internal power loss. A higher shunt impedance indicates a more efficient interaction between the mode and the beam. As with the quality factor, HOMs typically have lower R_s than the fundamental mode, reflecting their lower acceleration efficiency.

The shunt impedance in Eq. (5) is often referred to as *longitudinal shunt impedance*, denoted by $R_{s,z}$, as it is computed along a path parallel to the bunch direction.

C. Shunt vs Wake Impedance

There is a direct relation between the shunt impedance and the wake impedance (cf. [5, p. 346] or [6, p. 21]):

$$Z(\omega) = \frac{R_s}{1 + jQ\left(\frac{\omega}{\omega_r} - \frac{\omega_r}{\omega}\right)} \quad (6)$$

where Q is the quality factor and ω_r , the resonance frequency. At resonance, $Z(\omega_r) = R_s$. Since a cavity has several resonant modes, the total impedance is the sum over all modes (*cf.* [6, p. 21]):

$$Z(\omega) = \sum_n \frac{R_{s,n}}{1 + jQ_n \left(\frac{\omega}{\omega_{r,n}} - \frac{\omega_{r,n}}{\omega} \right)} \quad (7)$$

The real part of $Z(\omega)$ consists of narrow resonant peaks at frequencies with high quality factors $Q_n \gg 1$ —higher Q_n yield narrower peaks. These resonant peaks occur below the beam pipe’s lowest cutoff frequency; above it, energy escapes into the pipes, damping the oscillations and broadening and overlapping the peaks (see Figure 10).

Using Eq. (6) and Eq. (3), we define the *transverse shunt impedance*, $R_{s,\perp}$, as

$$R_{s,u} := \frac{|R_{s,z}^{\text{offset}} - R_{s,z}^0|}{u_{\text{offset}}} \quad (8)$$

D. Instability Threshold

TABLE I: Input data threshold impedances.

Parameter	ALBA	ALBA-II
Momentum compaction factor, α	8.88×10^{-4}	1.073×10^{-4}
Synchrotron frequency, f_s (kHz)	4.45	1.37
Longitudinal damping time, τ_s (ms)	3.1	6.9
Transversal damping time, τ_x (ms)	4.02	2.7
Transversal damping time, τ_y (ms)	5.2	5.8

To identify significant perturbations in the electron beam, we define thresholds for the longitudinal and transverse shunt impedances as

$$R_z^{\text{th}} = \frac{1}{N_C} \frac{1}{f_n} \frac{2E_0 f_s}{f_{\text{rev}} I_b \alpha \tau_s} \quad R_{x,y}^{\text{th}} = \frac{1}{N_C} \frac{1}{f_{\text{rev}}} \frac{2E_0}{I_b \beta_{x,y} \tau_{x,y}} \quad (9)$$

where N_C is the number of cavity locations in the Storage Ring, $f_{\text{rev}} = 1.12$ MHz, the revolution frequency, $I_b = 300$ mA, the beam current, $E_0 = 3$ GeV, the beam energy, and $\beta_x = 12.04$ m and $\beta_y = 8.13$ m, the betatron functions (*cf.* [3]). The remaining parameters differ for ALBA and ALBA-II and are listed in Table I. Here, the mode frequency f_n is treated as an independent variable. HOMs are expected to fall below these thresholds.

E. Computation

Due to the cavities’ complex geometry, the finite element software CST [1] was used to numerically compute each mode’s features. Two solvers were employed: the *Eigenmode Solver* and the *Wakefield Solver*.

The Eigenmode Solver (EMS) calculates the frequencies and corresponding electromagnetic field patterns

(eigenmodes) of a high-frequency structure. It accurately computes each mode’s Q -factor and shunt impedance R_s . The cavity’s beam pipe is simulated as an open boundary, since it connects to the vacuum chamber. To simulate the attenuation of electromagnetic waves in the dampers, we added *absorbers* at the ends (*cf.* [2]; see Figure 2, brown components). These are dissipative structures optimised to damp modes propagating through the waveguide, mimicking energy loss.

The Wakefield Solver (WFS) computes wake functions by simulating the electromagnetic fields induced by a bunch of charged particles traversing the structure along a main axis. Using a time-domain solver, it calculates these fields and then obtains the wake impedance via the Fourier transform of the wake function.

1. Approach

The EMS computes individual resonant modes of a structure, but as frequency and geometric complexity increase, the number of modes grows, making the process computationally expensive. However, most HOMs have very low Q and R_s , and thus have a negligible impact on beam stability. Conversely, the WFS is substantially faster, but less accurate. Due to this limitation, it mainly detects modes with sufficiently high Q and R_s to noticeably affect the beam.

Therefore, a two-step approach is employed: The WFS first computes the wake impedance and identifies frequency ranges with pronounced peaks in its real part. Then, the EMS is used to analyse those regions in detail, providing precise values for the shunt impedance and the quality factor.

IV. RESULTS

This section presents the simulation results for the three models. HOMs were computed up to 6 GHz for the 3HC models and up to 10 GHz for the full final model, based on the cutoff frequencies of the ALBA and ALBA-II beam pipes.

A. Single Harmonic Cavity

For the single harmonic cavity model (Figure 2), all HOMs were simulated using the EMS and compared with the WFS results to validate the approach described in Section III E 1.

Figure 3 compares the longitudinal shunt impedance from the EMS with the real part of the wake impedance from the WFS for frequencies above the fundamental (1.5 GHz). As expected, both solvers identify the same resonant frequencies, validating the method. However, the WFS results are less precise, with overlapping peaks forming broadband regions.

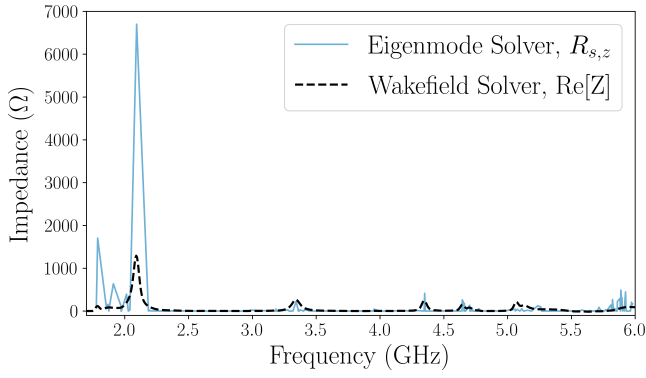


FIG. 3: Comparison between EMS and WFS impedances for a single 3HC. The plot shows frequencies above the fundamental (i.e., 1.5 GHz).

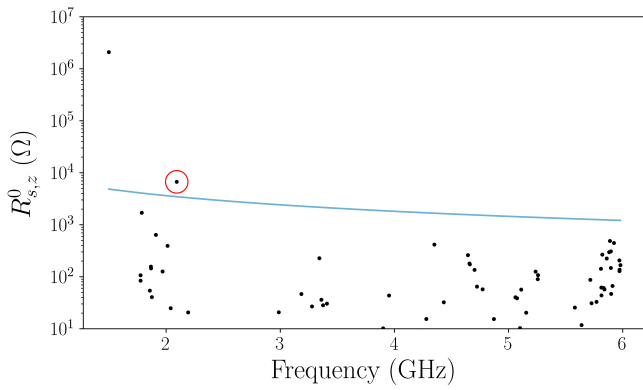


FIG. 4: Longitudinal shunt impedances of one 3HC for frequencies up to 6 GHz, including the fundamental mode. The blue curve represents the threshold $R_{s,z}^{\text{th}}$.

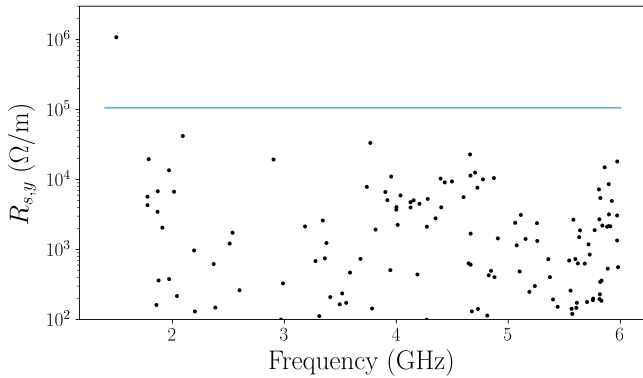


FIG. 5: Transverse shunt impedances of one 3HC for frequencies up to 6 GHz, including the fundamental mode. The blue curve represents the threshold $R_{s,y}^{\text{th}}$.

Figures 4 and 5 show the longitudinal and transverse shunt impedances, respectively, along with their thresholds. Only values above 10 Ω (resp., 100 Ω/m) are displayed. As expected, the fundamental mode exceeds

the threshold in both cases. A mode near 2.09 GHz, identified as the TM_{011} mode, also exceeds the longitudinal threshold (highlighted in Figure 4), meaning it might have a significant effect in the longitudinal direction. Thus, it requires further investigation. Nevertheless, it does not appear in Figure 5, indicating negligible transverse impact.

B. Double Harmonic Cavity

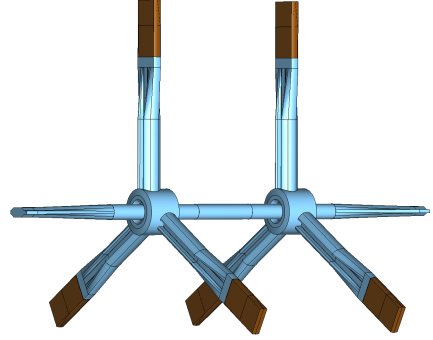


FIG. 6: Electromagnetic model for two 3HCs.

The electromagnetic model for the two 3HCs is shown in Figure 6. A taper connects the cavity beam pipe to the vacuum chamber, providing a smooth transition between their different geometries.

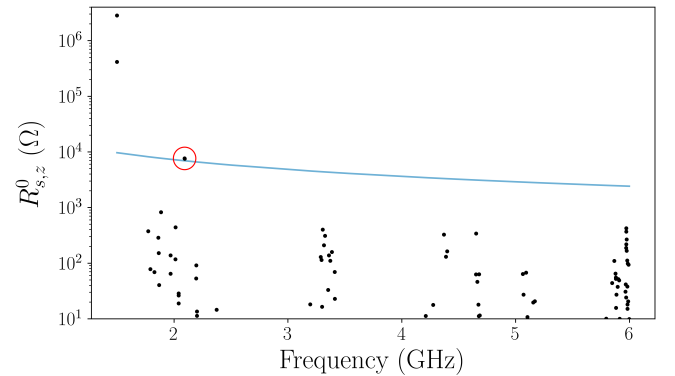


FIG. 7: Longitudinal shunt impedances of two 3HCs for frequencies up to 6 GHz, including the fundamental mode. The blue curve represents the threshold $R_{s,z}^{\text{th}}$.

Figure 7 presents the EMS results for the longitudinal shunt impedance, focusing on frequency regions identified by the WFS. The two highest values correspond to the fundamental modes of each cavity at ~ 1.5 GHz. Figure 8 displays the transverse shunt impedance for the two 3HCs models, confirming that no HOMs exceed the threshold. As in the model of a single 3HC, the TM_{011} mode (highlighted in Figure 7) slightly surpasses the longitudinal shunt impedance threshold, but remains below the transverse limit.

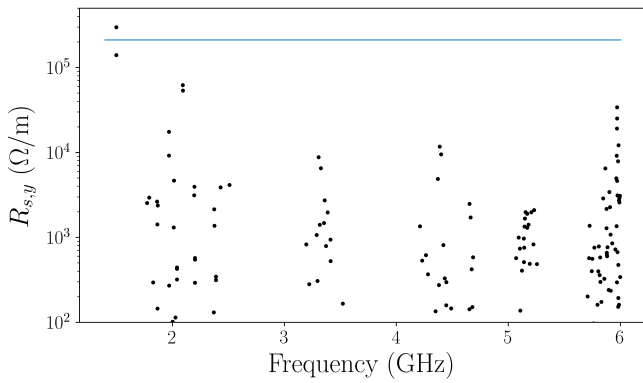


FIG. 8: Transverse shunt impedances of two 3HCs for frequencies up to 6 GHz, including the fundamental mode. The blue curve represents the threshold $R_{s,y}^{\text{th}}$.

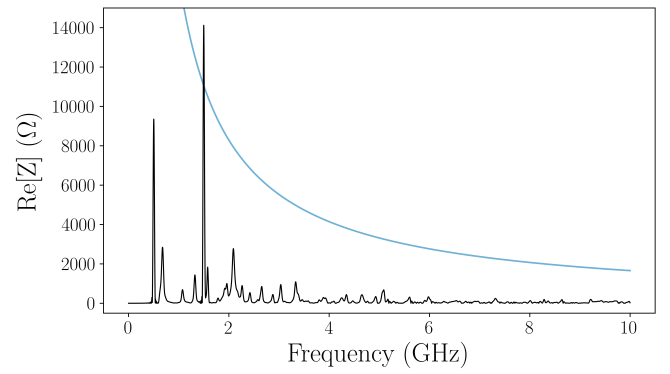


FIG. 10: Wake impedance for the final model. The blue curve represents the impedance threshold for ALBA-II.

C. Full Model

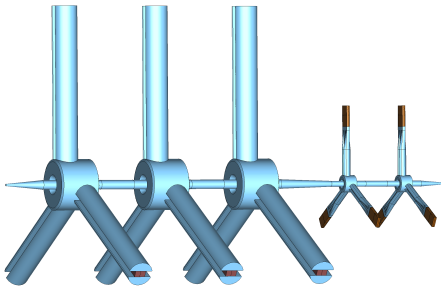


FIG. 9: Full electromagnetic model.

Figure 9 shows the final model. Tapers are used in the transition between cavities and at the ends of the full structure, connecting it to the beam pipe of ALBA-II, which will have a 16 mm diameter.

For this model, the study was conducted exclusively with the WFS, which computed the longitudinal wake impedance. Figure 10 displays the results alongside the threshold impedance. Two main peaks appear at 500 MHz and 1.5 GHz, corresponding to the fundamental modes of the Dampy and harmonic cavities, respectively. At higher frequencies, the modes are damped, producing lower and broader wake impedances.

V. CONCLUSIONS

Thanks to the incorporation of absorbers, we have developed realistic and computationally efficient models that accurately capture the electromagnetic behaviour of the RF cavities. For the single and double 3HC models, our analysis shows that the only higher-order mode producing a notable perturbation is the TM_{011} mode at approximately 2.09 GHz. However, its impact is only slightly significant in the longitudinal shunt impedance, with negligible transverse effects.

Future work will involve a deeper study of the TM_{011} mode, with the implementation of a more detailed electromagnetic model of the cavity, incorporating the tuner and the coupler. In addition, an Eigenmode analysis of the full model remains to be performed to achieve a comprehensive characterization of all relevant modes.

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Simulacions Electromagnètiques de les Cavitats de RF per ALBA II

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Resum: Aquesta tesi presenta una anàlisi electromagnètica dels modes d'ordre superior (HOMs) a les cavitats de radiofreqüència previstes per a la propera actualització d'ALBA-II. Utilitzant el *CST Studio Suite*, s'han realitzat simulacions de tres configuracions diferents amb cavitats de tercera harmònica de 1.5 GHz (pendent d'instal·lació) i cavitats *Dampy* de 500 MHz (actualment operatives). S'ha aplicat un estudi en dues etapes —combinant els *solvers* de *Wakefield* i *Eigenmode*— per identificar modes ressonants que podrien afectar l'estabilitat del feix. Els resultats mostren que tots els HOMs es mantenen per sota dels llindars d'impedància, excepte el mode TM_{011} a prop de 2.09 GHz, que supera lleugerament el llindar longitudinal i requereix una investigació més profunda.

Paraules clau: Radiofreqüència, cavitat harmònica, dinàmica del feix, impedància shunt.

ODSs: Aquest TFG està relacionat amb els Objectius de Desenvolupament Sostenible (SDGs)

Objectius de Desenvolupament Sostenible (ODSs o SDGs)

1. Fi de les desigualtats		10. Reducció de les desigualtats	
2. Fam zero		11. Ciutats i comunitats sostenibles	
3. Salut i benestar		12. Consum i producció responsables	
4. Educació de qualitat	X	13. Acció climàtica	
5. Igualtat de gènere		14. Vida submarina	
6. Aigua neta i sanejament		15. Vida terrestre	
7. Energia neta i sostenible		16. Pau, justícia i institucions sòlides	
8. Treball digne i creixement econòmic		17. Aliança pels objectius	
9. Indústria, innovació, infraestructures	X		

El contingut d'aquest TFG, part d'un grau universitari de Física, es relaciona amb l'ODS 4, i en particular amb la fita 4.4, ja que contribueix a l'educació a nivell universitari. També es pot relacionar amb l'ODS 9, fites 9.1 i 9.5, perquè fomenta la innovació i la construcció d'infraestructures fiables, sostenibles, resilents i de qualitat.