JINST
Published by IOP Publishing for Sissa Medialab

Received: *November 30, 2025*
Revised: *January 23, 2026*
Accepted: *January 26, 2026*
Published: *March 16, 2026*

17th Topical Seminar on Innovative Particle and Radiation Detectors
Siena, Italy
15–19 September 2025

Development of a multimode antenna for high-frequency gravitational waves based on bulk acoustic wave resonators

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Abstract: High-frequency gravitational wave detection based on a cryogenic bulk acoustic wave cavity coupled to a superconducting quantum interference device has been under investigation at the University of Western Australia for several years. A recent paper reported the observation of rare events of uncertain origin using the first antenna of this type. In this contribution, we describe the BAUSCIA project, a similar gravitational wave antenna at the University of Milano Bicocca, including the characterisation of commercially available bulk acoustic wave sensors, and plans to tailor those sensors to sample multiple frequencies from about 0.1 MHz to a few tens of MHz. Potential gravitational wave sources in this range include scenarios involving post-merger emission from neutron stars or emission from various dark matter candidates.

Keywords: Cryogenics and thermal models; Resonant Detectors

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https://doi.org/10.1088/1748-0221/21/03/C03025

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1 Introduction and physics motivation

The direct observation of gravitational waves by the LIGO and VIRGO experiments marked the beginning of a new era of astrophysical investigation, enabling tests of gravitation and imposing new constraints on astrophysical models. Among the many exciting frontiers opened by these discoveries, one particularly promising avenue is the exploration of high-frequency gravitational waves (HFGWs), a domain that remains largely uncharted due to current technological limitations. Predicted HFGW sources include dark-sector or beyond-SM scenarios (e.g. ultralight fields, planetary-mass primordial black hole binaries), QCD-scale physics in neutron-star post-mergers, and other compact-object or primordial processes. A detection in the MHz band would be both complementary and supplementary to km-scale interferometers, enabling multi-band studies and targeted coincidence searches with electromagnetic counterparts [1].

The instrumental technique presented here consists of high-frequency acoustic resonant cavities realized with piezoelectric crystals: Bulk Acoustic Wave Sensors for High-frequency Antennas (BAWSHA, dubbed BAÙSCIA in the local dialect).

Quartz Bulk Acoustic Wave (BAW) resonators provide exceptionally high mechanical quality factors in compact devices and exhibit well-understood piezoelectric transduction. Their multi-mode, narrow-band response can be leveraged through arrays covering many overtones and thicknesses to reach frequencies across more than two decades in the MHz range. The BAUSCIA program builds on and complements the MAGE effort at the University of Western Australia (UWA) [2] with the goal of establishing a global HFGW network.

2 Methodology: BAW working principle

Bulk acoustic wave (BAW) resonators are piezoelectric devices widely used in precision time-control, where they are valued for their ability to sustain mechanical vibrations at MHz frequencies with exceptionally high quality factors. When operated at cryogenic temperatures, quartz BAWs routinely reach Q-factors above 10^7–10^8 in the 5–20 MHz range [3], making them attractive candidates for HFGW detection [4]. Their performance stems from the combination of high acoustic frequencies, low internal dissipation, and strong electromechanical coupling arising from the intrinsic piezoelectric properties of quartz.

In a BAW resonator, a piezoelectric crystal is sandwiched between electrodes so that mechanical vibrations generate an electric charge on the plates. Several families of acoustic modes exist, including longitudinal (A) modes and fast/slow shear (B and C) modes. Only odd overtones of these modes produce a net piezoelectric response, and these are the frequencies at which the device is most sensitive. An incoming gravitational wave acts as a periodic tidal force on the crystal, producing an electrical signal that can be read out by a SQUID (Superconducting Quantum Interference Device), an ultra-low-noise device commonly employed for current and magnetic-flux amplification in cryogenic detectors.

The resonance spectrum is primarily set by the crystal shape, thickness and elastic phase velocities. By choosing a set of thicknesses and exploiting several overtones per device, multiple narrow bands can be monitored at the same time with a single BAW.

3 Design of the BAUSCIA antenna

The conceptual design of BAUSCIA [6] builds upon the pioneering developments that enabled the MAGE experiment, extending them toward a truly multimode and scalable architecture. A central goal of the project is to achieve sensitivity over more than two decades in frequency, thereby overcoming the intrinsically narrow-band response of individual resonant-mass detectors. This is accomplished by combining two complementary classes of resonators: commercially available quartz BAWs, optimized around the third overtone near 5 MHz and used for early operation and benchmarking, and set of custom quartz resonators based on different crystal orientations selected to maximize both the piezoelectric response of quartz and the stability of their performance. To support broad spectral coverage, the apparatus is designed around a modular layout, allowing the deployment of multiple resonators and independent SQUID readout channels. This modularity enables the progressive expansion of the system toward an array comprising $\mathcal{O}(10)$ sensors sampling $\mathcal{O}(100)$ distinct acoustic resonances. Such an arrangement provides the frequency multiplicity required for gravitational-wave searches in the MHz regime, while ensuring flexibility in device configuration, readout optimization, and integration of future custom BAWs.

The BAW resonators will be operated in a dilution refrigerator, where temperatures in the millikelvin regime can be reached. Such conditions are essential to suppress thermal noise and to maximize the mechanical quality factors of the resonators, thereby enhancing the strain sensitivity of the detector and ensuring optimal performance of the SQUID readout. The front-end will employ two-stage DC-SQUIDs, while the back-end will be implemented on a Radio Frequency System-on-Chip (RFSoC) class FPGA (Field Programmable Gate Array), integrating high-speed analog-to-digital converters and programmable logic to realize a fully digital lock-in architecture. The firmware will provide both continuous and triggered acquisition and it will allow simultaneous monitoring of multiple narrow-band channels on a single line, easily enabling scalable expansion to additional sensors.

4 Project status and sensitivity projections

4.1 BAW resonators

To begin the development of the BAUSCIA detector, a set of commercial quartz BAW resonators designed to operate around 5 MHz was first procured from Rakon Ltd.[1] These devices were then extensively characterized, both at room temperature and under cryogenic conditions, to assess their resonance behavior and overall performance. Figure 1 shows the measured quality factor Q as a function of the resonance frequency for a representative subset of modes operated at cryogenic temperature (approximately 30 mK). The quality factor of each acoustic mode is defined as $Q = f_0/\Delta f$, where Δf is obtained from the full width at half maximum of the measured resonance peak and provides a direct measure of acoustic energy dissipation in the resonator. The distribution highlights a wide spread of quality factors across different overtone families, with several modes exceeding 10^7, reflecting mode-dependent acoustic loss mechanisms and confirming the excellent acoustic performance of these commercial devices and their suitability for the first BAUSCIA prototype.

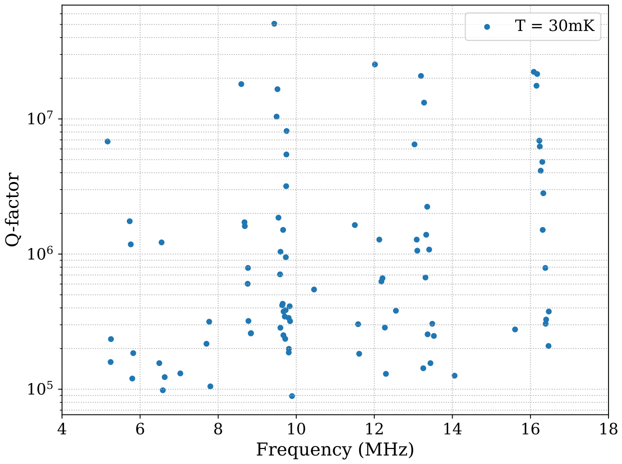

Figure 1. Measured quality factor Q as a function of resonance frequency for a commercial quartz BAW (Rakon Ltd.) operated at cryogenic temperature (approximately 30 mK).

These commercial quartz resonators are now ready to be operated inside the dilution refrigerator, for the upcoming measurement campaign. They will form the initial reference sensors of the experiment and will also be used for planned coincident data-taking with the MAGE setup.

Meanwhile, in collaboration with the company Cristal Innov[2] (France), we have procured SC-cut and AT-cut quartz blanks, specifically designed for BAUSCIA. The SC (stress-compensated) cut is a crystallographic orientation designed to reduce sensitivity to mechanical stress and temperature variations, while the AT (angle-thickness) cut provides efficient piezoelectric coupling and robust resonant behavior. A set of eight SC-cut crystals covering thicknesses from ~2 mm to ~27 mm has been produced (see figure 2). Each crystal has a 25×25 mm^2 cross-section and is designed to cover a wide range of resonant frequencies for the BAUSCIA resonators prototypes. AT-cut BAWs are being developed in parallel as a complementary benchmark for coupling and manufacturability.

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[1] `https://www.rakon.com/`.

[2] `https://www.cristal-innov.com/en/products-cristal-innov/quartz-cristal-innov-uk.html`.

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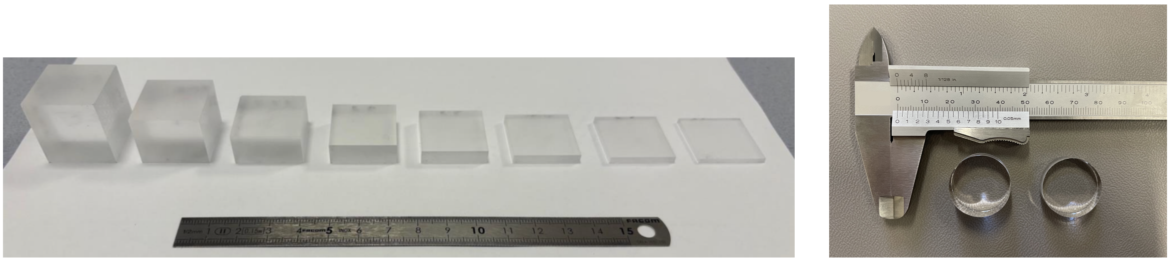

Figure 2. Quartz blanks produced for the BAUSCIA project. *Left*: SC-cut quartz blanks of different thicknesses (from 2 mm on the right to 27 mm on the left), used to span acoustic frequencies from a few hundred kHz to several MHz. *Right*: example of SC-cut quartz blanks manufactured for BAUSCIA, after the first phase of shaping and polishing.

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4.2 Cryogenic infrastructure and SQUID noise characterization

The dedicated dilution refrigerator for the BAUSCIA experiment was installed and commissioned in Spring 2025 at the Physics Department of the University of Milano-Bicocca, reaching a base temperature of about 9 mK and providing sufficient cooling power to operate both the BAW resonators and the SQUID readout electronics under stable cryogenic conditions. In parallel, the DC-SQUID devices are undergoing a detailed characterization campaign that includes measurements of flux-noise density, gain, dynamic range, and optimal operating parameters. The BAUSCIA readout employs DC-SQUID devices from the company Magnicon[3] with an input inductance of 400 nH and bandwidths of about 20 MHz in flux-locked-loop mode and 50 MHz in open-loop operation. Figure 3 summarizes the current status of the SQUID noise characterization and its impact on the expected detector performance. The left panel shows the measured noise power spectral densities of three independent DC-SQUID readout channels operated at 100 mK, providing a direct assessment of the intrinsic readout noise and channel-to-channel variations. The right panel compares the measured intrinsic

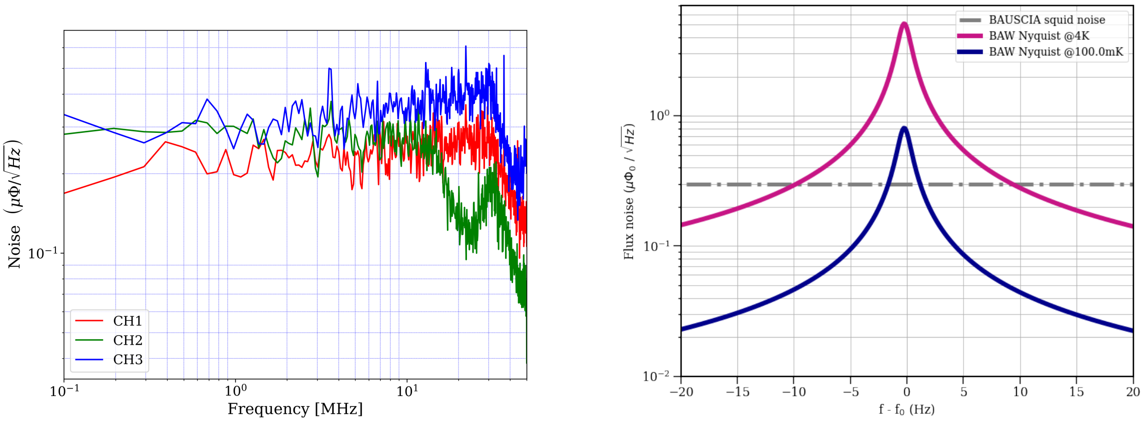

Figure 3. *Left*: noise power spectra measuresd at 100 mK for three SQUID channels used in the BAUSCIA readout. *Right*: expected noise budget for a representative BAW overtone. The thermal (Nyquist) noise of the resonator at 4 K (magenta) and 100 mK (blue) is compared with the intrinsic flux noise of the measured BAUSCIA DC-SQUID readout (grey dashed line).

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[3] http://www.magnicon.com/squid-sensors.

SQUID flux noise with the expected thermal Nyquist noise [5] of a representative BAW overtone at different temperatures, illustrating the relative contributions of readout and resonator noise in the present operating conditions. For this illustrative example, evaluated for the $n = 3$C overtone, corresponding to the third compressional bulk acoustic mode, the calculation assumes a 5 MHz BAW resonance with $Q = 10^7$ and an effective mass of 0.2 mg. At 100 mK the SQUID noise remains below the expected thermal noise of the resonator, so no SQUID-limited performance is expected at this operating temperature. Any transition to a SQUID-limited regime will be assessed based on the final operating conditions of the setup.

4.3 Projected strain sensitivity

The projected strain sensitivity of the BAUSCIA detector has been estimated using the formalism presented in ref. [6]. For a mode with resonant frequency ω_λ, quality factor Q_λ, temperature T_λ and effective mass m_λ, the peak single-sided strain spectral density is given by

$$S_h^+(\omega_\lambda) = \frac{2}{\bar{\xi}_\lambda d}\sqrt{\frac{k_b T_\lambda}{m_\lambda Q_\lambda\, {\omega_\lambda}^3}} \quad [\text{strain}/\sqrt{\text{Hz}}], \tag{4.1}$$

where k_b is the Boltzmann constant, $\bar{\xi}_\lambda$ is the coupling between the impinging GW and the acoustic mode of the cavity and d is the thickness of the resonator. Using experimentally measured values at cryogenic temperatures for Q_λ and for the coupling parameters, the commercial Rakon devices are expected to reach peak sensitivities in the $\mathcal{O}(10^{-22})$ strain/$\sqrt{\text{Hz}}$ when operated at tens of mK.

These projections indicate that already the first BAUSCIA deployment, based on commercial resonators, will achieve competitive sensitivity in the MHz region. The integration of custom SC-cut and AT-cut devices, featuring larger effective mass and improved phonon confinement, is expected to further enhance performance and provide sensitivity to currently inaccessible regions of the high-frequency gravitational-wave spectrum.

5 Future plans and outlook

The BAUSCIA detector will enter its operational phase in 2026 with the first cryogenic measurement campaign using commercial Rakon BAW resonators. This initial deployment will benchmark the full readout chain and will allow coincident data taking with the MAGE experiment at UWA. Such a multi-site configuration enables unique background-rejection strategies and will provide the first search for HFGW using geographically separated acoustic antennas.

In parallel, the custom resonators will be fabricated, equipped with cryogenic electrodes and commissioned. Their integration into the experimental setup will constitute the second phase of BAUSCIA, aimed at realizing a multimode antenna with $\mathcal{O}(10)$ optimized resonators sampling $\mathcal{O}(100)$ distinct frequencies. In this second phase of the experiment, BAUSCIA will push the strain sensitivity below the 10^{-22} strain/$\sqrt{\text{Hz}}$ regime at selected modes opening a new observational window for HFGW searches. Figure 4 places the BAUSCIA strain sensitivity in the broader context of current and planned gravitational-wave detectors. In addition to the detector sensitivity curves, the figure includes representative astrophysical strain signals overlaid for reference, following the approach presented in [7]. These include primordial black hole (PBH) merger signals for different PBH masses at fixed reference distances. The labels shown at the top of the figure indicate the characteristic

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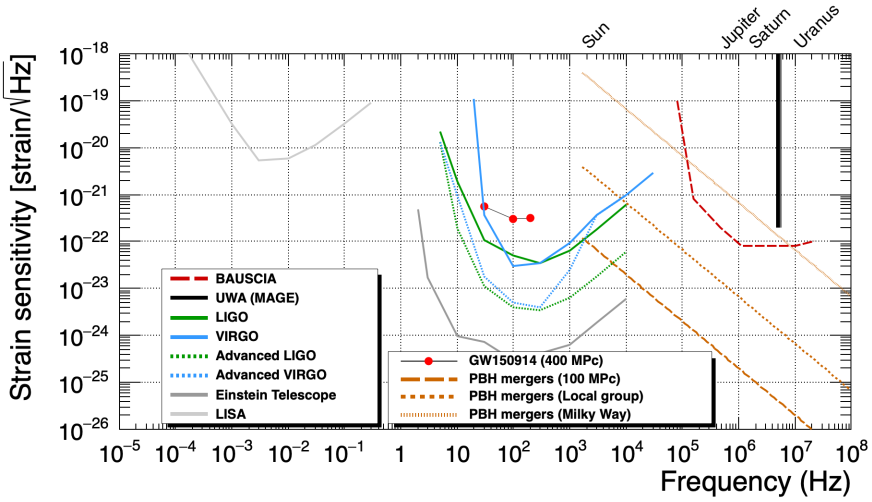

Figure 4. Strain sensitivity of bulk acoustic wave (BAW) gravitational-wave detectors. The black vertical line shows the narrow-band sensitivity of the single-mode BAW antenna operated at UWA, while the dashed red curve indicates the projected broadband sensitivity of a multimode BAW array as envisaged for BAUSCIA. Representative astrophysical strain signals from primordial black hole (PBH) mergers are overlaid for reference. Reproduced from [6]. CC BY 4.0.

frequencies expected for PBH mergers with masses comparable to those of the Sun and of the planets in the Solar System. The black vertical line represents the measured narrow-band sensitivity of one of the acoustic modes of the BAW antenna operated by the MAGE experiment at UWA, shown here as a representative example, intrinsically sensitive only within a narrow frequency range around its resonance. In contrast, the dashed red curve illustrates the projected broadband sensitivity of a multimode BAW array as envisaged for BAUSCIA.

Overall, the preliminary results presented in this work demonstrate the feasibility of the BAUSCIA approach and provide a solid experimental basis for the development of a first-generation multimode BAW gravitational wave detector.

Acknowledgments

This work is supported by the Italian Ministry for Universities and Research (MUR), “Dipartimenti di Eccellenza 2023–2027” and by the PNRR MUR Project (PE0000023-NQSTI). We acknowledge the MAGE team (UWA) for guidance and shared developments.

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