# Making a Modern GW Resonant Bar Detector: The He-BAR

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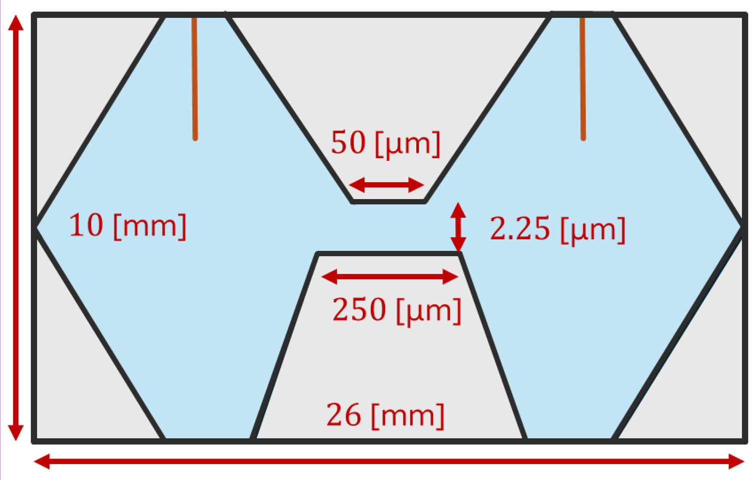
## Introduction




The momentous detection of gravitational waves first occurred in 2015 with the advanced LIGO interferometers. Now there are 4 successful observatories with a series of increasing landmark detections, however the detection sensitivity is focused between approximately 20 to 1000 Hz. There have been a series of new detectors –both proposed and implemented– which attempts to investigate these regions of frequency space the field is blind to. We present work showcasing the recipe to build a resonant bar style detector with superfluid $^4$He and optomechanical readout; with improvements to the general theory of this style of detector. Our specific design improves the frequency shift parameter -which characterising the readout coupling sensitivity- with a re-entrant style design by maximising the overlap integral of EM and Mechanical modes. This poster displays the experimental setup, characterisation, and resulting noise floor of the prototype low-temperature He-BAR detector (Helium Bulk Acoustic Resonator).

Figure 1 (left): Diagram of the aluminium cavity with dimensions, helium, and antennas.

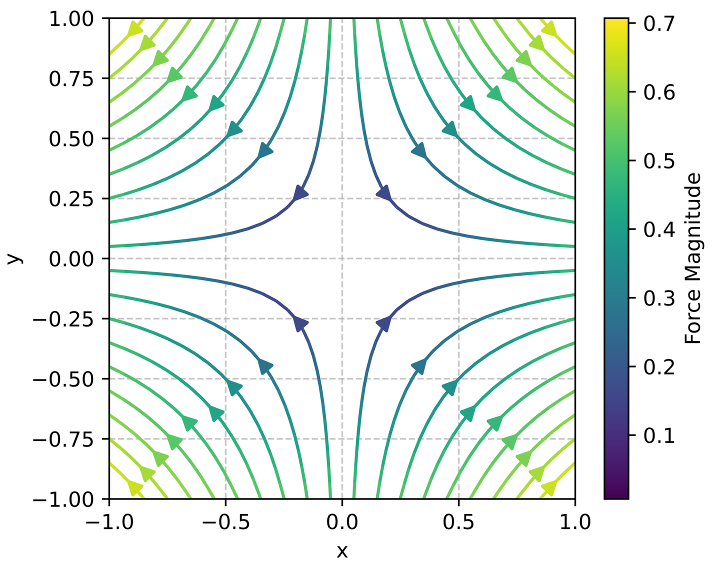
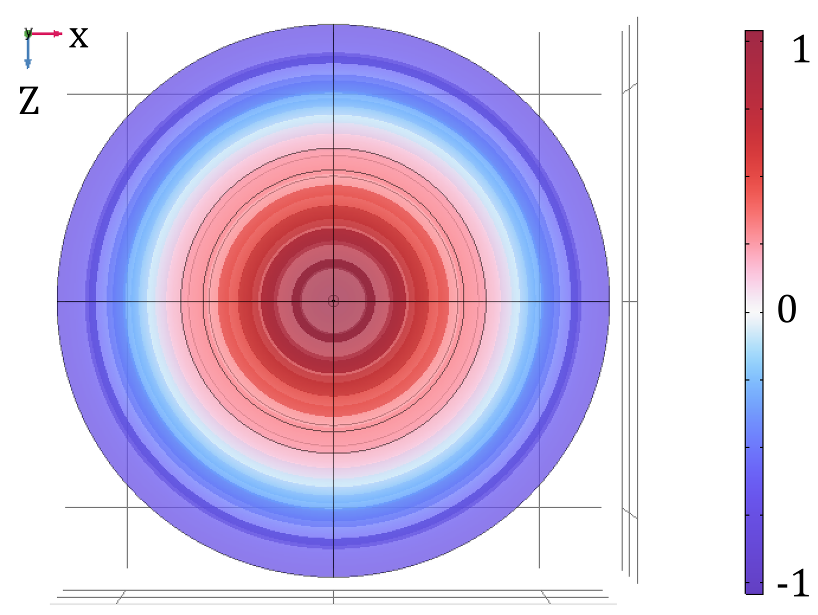



Figure 2 (right): The force lines of an incoming gravitational wave of the plus polarisation at an instant of time.

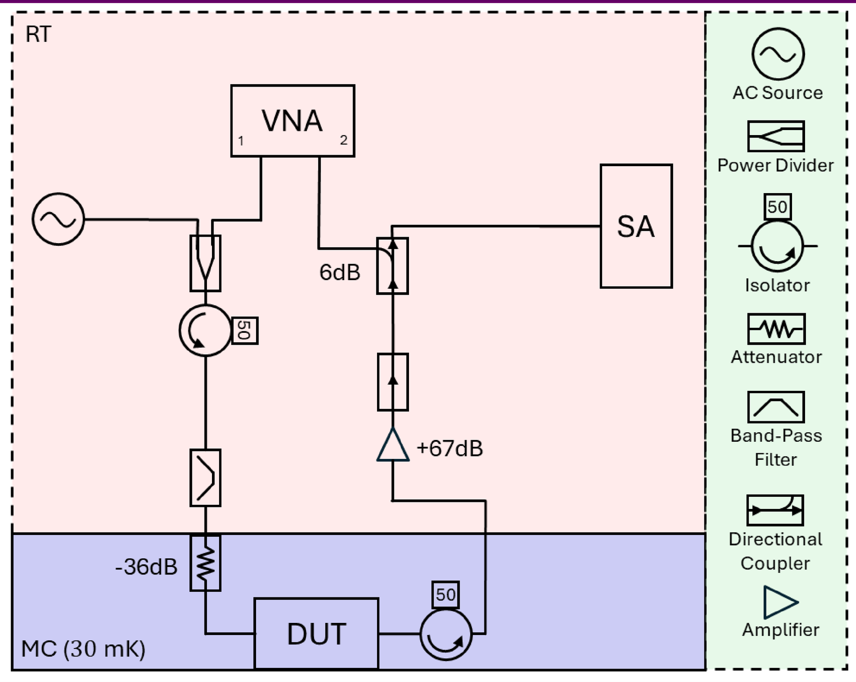
## Experimental Setup




The experiment involves an Aluminium re-entrant cavity –the pillars of which confine the EM mode– filled with superfluid $^4$He -shown Fig. 1. The cavity is inside a copper immersion cell which is filled via a fill line and placed inside a dilution refrigerator. The EM mode is coupled to with two brass antennas. A specific mode of the helium is chosen due to it's sensitivity to both an in-coming gravitational wave and coupling to the EM mode -eigenmode studied here is shown in Fig 3. The density fluctuations of the helium are then read-out optomechanically via an amplitude and phase modulated pump tone applied on the resonance frequency with the RF circuit shown in Fig. 4.

Figure 3 (left): Finite element model simulations of the unnormalized spatial pressure mode for the re-entrant cavity with a frequency of 14.4 kHz.

Figure 4 (right): RF diagram of the circuit, featuring a delineation between the room temperature and fridge sections.




## Experimental Results

To achieve a precise and accurate readout of the motion we characterise the EM and mechanical modes along with the frequency shift parameter ($G$). We measured a total decay rate of down to $\kappa_{tot}/2\pi = 90$ kHz. Our cavity is under-coupled with $\kappa_{ext}/\kappa_{tot} \approx 0.01$ and has a resonance frequency of 6.19 GHz; example resonance shown in

$$S_{21}(\omega) = \frac{\kappa_{\rm ext}}{\kappa_{\rm tot} - 2i(\omega - \omega_{\rm cav})} \quad (1)$$

$$S_{\xi\xi} = \frac{4k_{\rm B}T\Gamma_{\rm m}}{m_{\rm eff}\Omega_m^2}\frac{1}{\Gamma_{\rm m}^2 + 4(\Omega - \Omega_m)} \quad (2)$$

$$G \propto \frac{\int \eta_P(x,y,z)\,|E(x,y,z)|^2\,{\rm dV}}{\int \eta_P(x,y,z){\rm dV}} \quad (3)$$

measured displacement spectral density for varying pump powers. The amplitude dependence after 0 dBm is indicative of phase noise effective heating from the pump. The measured value of $G$ agreed with the theoretical value simulated using finite element methods to within the measured uncertainty $G$ = -0.137±0.008 Hz/pm. We increased this due to the re-entrant pillars confining the EM mode with simulations indicating a doubling of the overlap integral shown in Eq. 3.

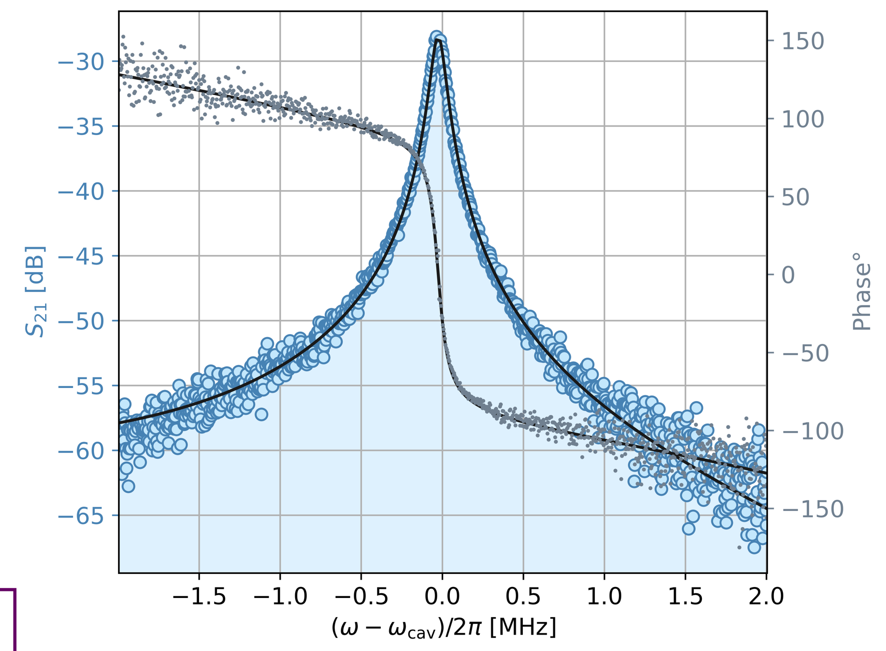



Figure 5: Example $S_{21}$ measurement of the cavity resonance fitted with equation from.

Fig 5. The mechanical resonance investigated was measured to have a resonance frequency of 14.5 kHz and Q = 4.38×10$^5$. Fig. 6 shows the

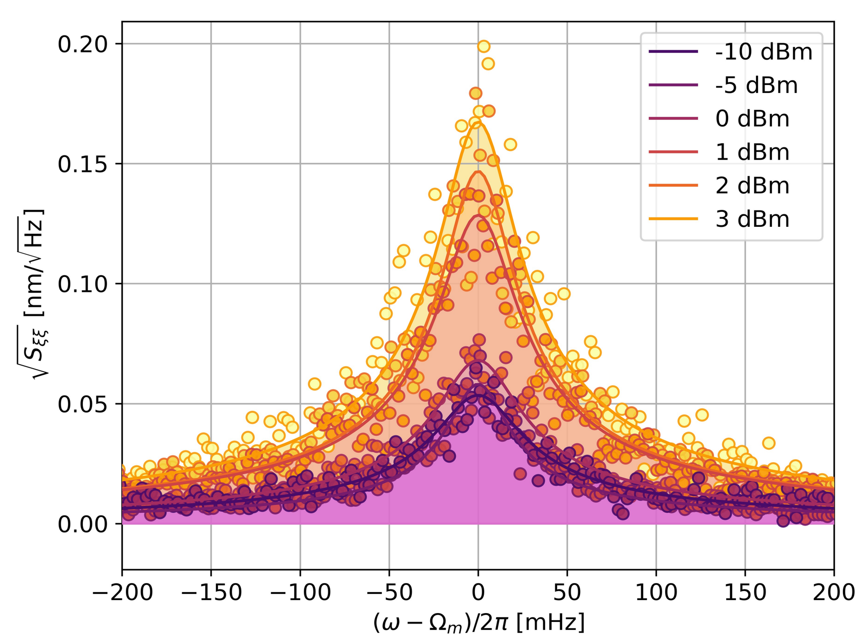



Figure 6: Measured displacement spectral density for varying pump powers.

## Gravitational Wave Sensitivity

$$h_{ij}^{TT}(t,z) = \begin{pmatrix} h_+ & h_\times & 0 \\ h_\times & h_+ & 0 \\ 0 & 0 & 0 \end{pmatrix}_{ij} \cos\left[\omega(t - z/c)\right] \quad (4)$$

$$\frac{\tilde{\xi}_n}{\tilde{h}} = \mathcal{T}(\omega)_{n,\xi} = \frac{\omega^2(q_{n,xx} - q_{n,yy})}{4m_{\rm eff}[\Omega_m - \Omega^2 + i\Gamma_{\rm m}\omega]} \quad (5)$$

$$S_{nn}^{hh} = \frac{|\mathcal{T}_{n,\xi}|^2}{S_{\xi\xi}} \quad (6)$$

$$S_{nn}^{hh} = \frac{4k_{\rm B}T\Gamma_{\rm m}}{L_{\rm eff}^2\omega^2 m_{\rm eff}} \quad (7)$$

$$L_{\rm eff} = \frac{q_{xx} - q_{yy}}{4m_{\rm eff}} \quad (8)$$

We transformed the measured displacement spectral density corresponding to −5 dBm shown in Fig. 6 to the noise equivalent strain spectral density; this and theoretical noise contributions are shown in Fig. 7. Eq. 4 is the matrix of a gravitational wave. The process finding the sensitivity is shown in Eqs. 5 and 6, with 7 and 8 being the theoretical contribution due to thermal noise. We have achieved a good sensitivity considering the lack of acoustic isolation. We know the response of a mechanical mode due to a gravitational wave by the theory presented in [1] which describes $q_{ii}$ variables. In [2] there are descriptions of the theoretical noise contributions from shot and back action noise which we have similarly converted to show the contribution to our prototype's noise floor. By adding adequate acoustic isolation to reduce the acoustic noise we should be able to effectively remove this contribution. The thermal motion can be reduced both optomechanically and by increasing the quality factor to those shown in previous work on superfluid helium [3]. This should reduce the noise floor to close to 10$^{-20}$.

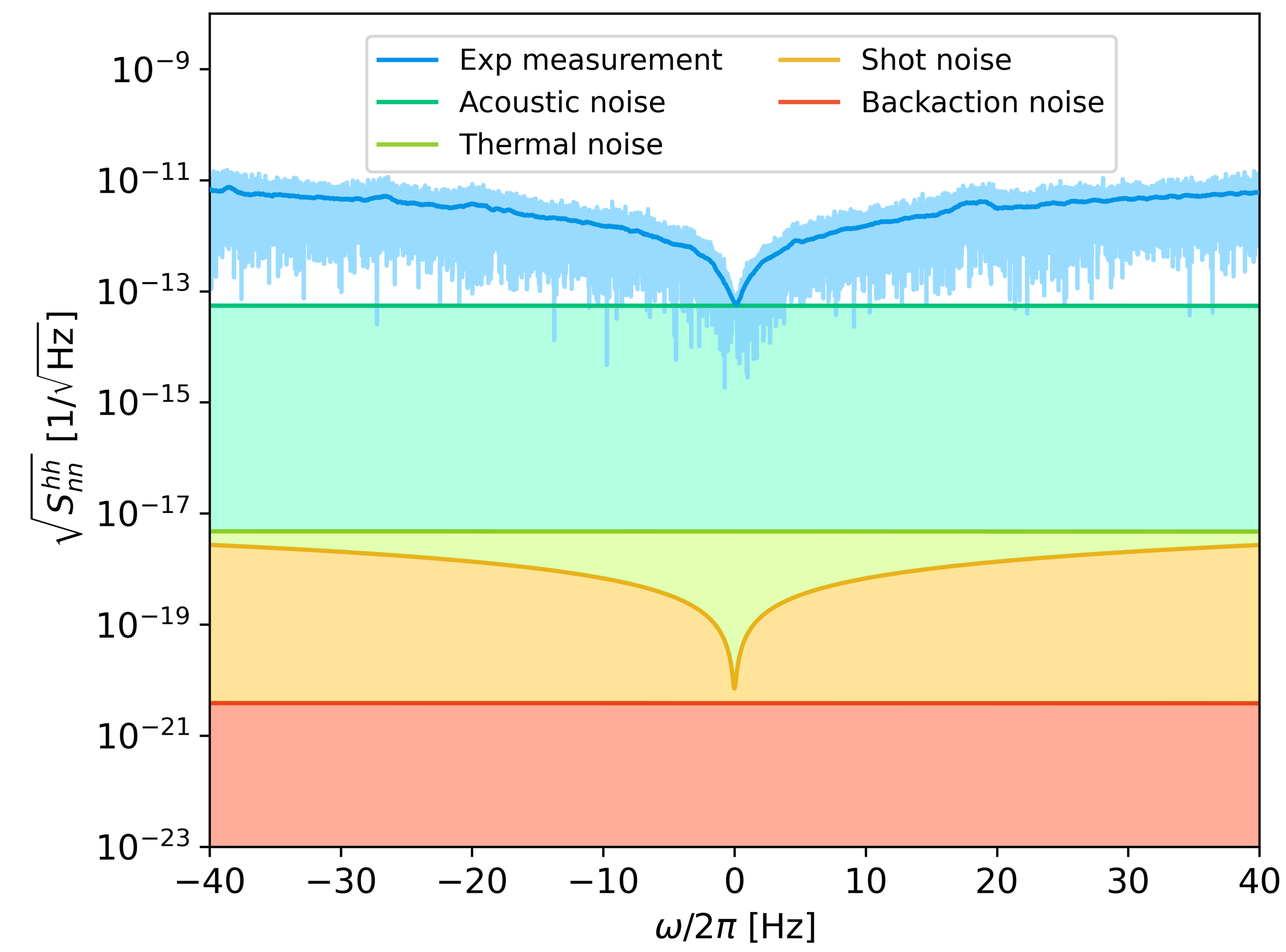



Figure 7: noise-equivalent strain power spectral density with theoretical noise contributions shown. The dark line for 'Exp measurement' is a rolling average.

## Conclusion

We have developed and tested a superfluid helium-filled re-entrant cavity optomechanical system, the He-BAR, as a platform for gravitational wave detection. The system demonstrates a minimum noise-equivalent strain spectral density of 6×10$^{-14}$, with current limitations due to lack of mechanical vibration isolation. With the re-entrant geometry, an improvement in optomechanical coupling strength is achieved through enhanced spatial mode overlap. Improving mechanical isolation and increasing quality factors, offers a realistic path to strain sensitivities of 10$^{-20}$, making it a promising candidate for future high-frequency gravitational wave detection. Furthermore, a superfluid-based resonant bar enables unique design freedoms, including frequency tunability, low mechanical dissipation, and high spatial mode control, which in the future could underpin novel detector architectures for targeting a wide range of gravitational waves from low to high frequencies with scalable, compact designs.

More information

## References

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