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Virgo's Quantum Noise Reduction System: Current Status and Future Insights

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Quantum noise poses a fundamental limitation to the sensitivity of second-generation terrestrial gravitational wave detectors,affecting both low and high frequencies through radiation pressure noise and shot noise, respectively. Overcoming this challenge is crucial for advancing to third-generation detectors such as the Einstein Telescope.

Since the third observation run (O3), both LIGO and Virgo implemented a quantum noise reduction system. By employing a Frequency Independent Squeezing (FIS) vacuum source, they achieved a $\sqrt{2}$ improvement in high-frequency sensitivity, resulting in a 5-8% increase in their astrophysical reach for Virgo [1] and 12-14% for Ligo [2]. However, this improvement came at the cost of increased radiation pressure noise in the 20-40 Hz range, limiting further noise reduction at higher frequencies. [3] [4].

In the O4 scientific run, LIGO and Virgo addressed this limitation by developing a Frequency Dependent Squeezing (FDS) source; both of the systems are based on a filter cavity to induce frequency rotation to FIS states. While LIGO successfully integrated FDS [5], Virgo encountered challenges related to technical noise and misalignment of the signal recycling cavity, restricting its implementation to FIS during O4b. Nevertheless, Virgo extensively tested and commissioned the FDS system in standalone mode with a homodyne detector [6]. Despite these challenges, Virgo's experience with FDS installation provided valuable insights for future detectors, particularly in the development of the Einstein Telescope's quantum noise reduction system.

This presentation aims to discuss the status of Virgo's Quantum Noise Reduction system at the beginning of the O4b scientific run, highlighting encountered challenges and adopted solutions that could be taken into account in the design of the ET FDS system. Notable issues found include the dependence of the filter cavity RTL on the optical axis, challenges in controlling the Filter Cavity detuning with the 1.2 GHz frequency shifted subcarrier beam, variations in relative detuning between green and infrared beams with mirror temperature when they are used to control in length the filter cavity, and issues induced by stray light.

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