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# A Prototype Interferometer for 3rd Generation Detectors: the Glasgow Cryogenic Interferometer Facility

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**Abstract.** The current generation of gravitational wave detectors revolutionised the scientific community with the first direct detection of gravitational waves in 2015. The next generation of detectors will utilise innovative techniques to improve detector sensitivity, with prototype interferometer facilities are of fundamental importance to investigate and realise these technologies. One prototype working to this goal is the Glasgow Cryogenic Interferometer Facility. This facility will utilise a double-cavity configuration with cryogenic silicon optics to demonstrate necessary technologies for these next-generation detectors. This work outlines a design for the cryogenic silicon suspension and details the ongoing experimental work at the facility.

## 1 Introduction

Next gravitational wave detectors have ambitious goals for detector sensitivity, aiming for a 10× increase in comparison to current sites [1, 2, 3]. To reach such goals, these detectors have innovative designs which build upon tested technologies and implement new techniques such as cryogenic cooling of the mirrors, which requires materials with low thermal noise and high thermal conductivity at low temperatures such as crystalline silicon or sapphire. For example, the design for LIGO Voyager [4] proposes the installation of silicon test masses and cooling cavity optics to 123 K, where silicon has a thermal expansion null, with a laser wavelength of 2000 nm for compatibility with silicon optics. The Einstein Telescope [3] will have two nested detectors to optimise for sensitivity to both low-frequency and high-frequency gravitational waves, with the cryogenic low-frequency detector (ET-LF) requiring silicon optics and suspensions, a laser wavelength of 1550 nm, and an operation temperature of $10 - 20\,\mathrm{K}$.

Interferometer facilities are crucial for demonstrating the feasibility and compatibility of these technologies in an interferometer configuration, without affecting the observation time of current detectors. There are several prototype facilities in operation with each site having differing priorities and capabilities, and operating in collaboration for current and future detectors [5, 6, 7, 8].

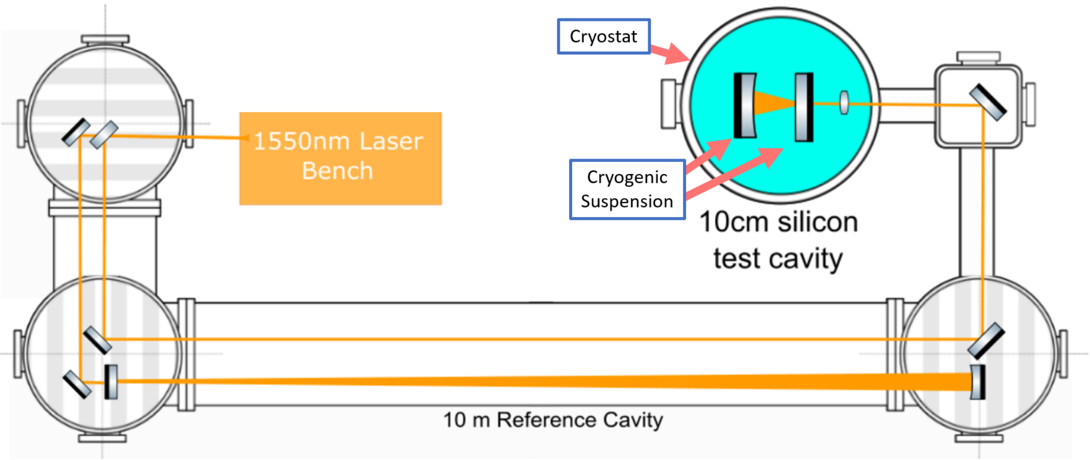

Figure 1: Glasgow Cryogenic Interferometer Facility layout showing the 10 m room temperature reference cavity for laser stabilisation and the 10 cm cryogenic test cavity for silicon suspended optics.

### *1.1 The Glasgow Cryogenic Interferometer Facility*

The Glasgow Cryogenic Interferometer Facility (GCIF) such a prototype which has undergone a recent upgrade with infrastructure works completed in 2024. The facility will consist of one 10 m room-temperature reference cavity, followed by a shorter 10 cm cryogenic cavity with suspended silicon optics, and is targeting the demonstration of several technologies required for ET-LF. The layout is shown in Figure 1. Site aims include demonstrations of 1550 nm laser amplification and stabilisation; test mass cooling to 18 K and 123 K with heat extraction by thin crystalline fibres; low thermal noise fibres and jointing; seismic isolation from cryo-cooler noise by passive and active filtering; interferometric controls and sensing of a cryogenic suspended cavity; and direct measurements of coating and suspension thermal noise – a critical step for proving the viability of future detectors.

## 2 Cryogenic Suspension Conceptual Design

The conceptual design of the cryogenic silicon suspension is shown in Figure 2(a). From the cryostat cold plate, six blade springs will suspend a metal common upper platform (CP) using steel wires. Blade springs on the CP will give vertical seismic isolation to each double-chain, with metal wires used between the CP and each penultimate mass. The two double-stage test chains, each comprising of a penultimate mass and a test mass, will be hung from the CP to form the cryogenic test cavity. The penultimate and test masses will be 1 kg high-purity float-zone silicon. The final stage will be entirely crystalline: in one concept, sapphire ears will be hydroxide-catalysis bonded to the penultimate and test masses, and thin sapphire fibres will be welded to the ears to suspend the test masses as shown in Figure 2(b) and (c). A second concept utilises silicon fibres which are widened at each end to ‘necks’ as shown in Figure 2(d), which would be hydroxide-catalysis bonded to the masses. The choice of fibre material is motivated by the cryogenic material properties, the fabrication feasibility and jointing technology readiness.

### *2.1 Dynamical suspension modelling*

The first phase of the cryogenic suspension design used a dynamical suspension model, created in Mathematica [12]. This model was crucial in exploring the resonant modes of the triple suspension system and the transfer of seismic ground motion to predicted test mass motion. Design elements such as wire lengths, wire attachment points, and masses could be easily modified to minimise suspension resonance peaks in the experimental sensitivity band, and optimise seismic attenuation from the cryostat to the optics [13]. This model is currently in use to map seismic isolation performance of the system including degree of common motion rejection of seismic noise due to the inclusion of a common upper suspension stage from which both test mass suspension chains hang, and to aid local control through the improvement of selected mode visibility.

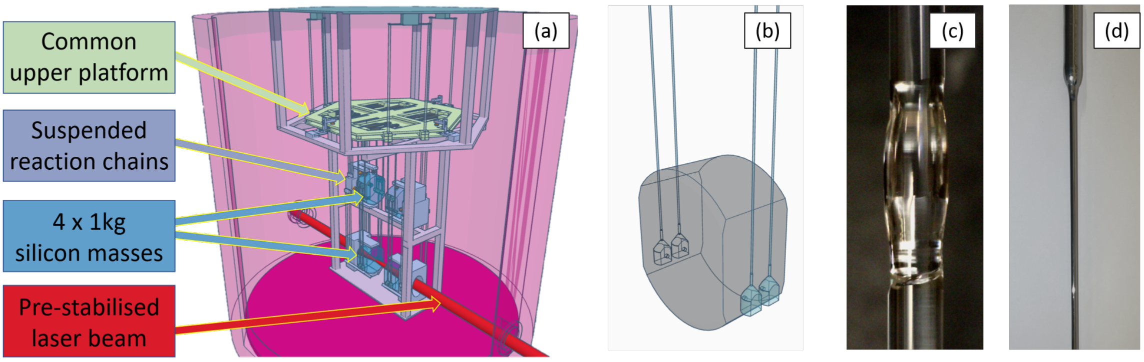

Figure 2: (a) Computer-aided design mock-up of cryogenic suspension shown suspended in the GCIF cryostat (pink). (b) A conceptual design for the fibre-mass attachment. Sapphire fibres are welded to sapphire ears, which are bonded to the silicon test masses [9]. (c) Weld region of a sapphire fibre [10]. (d) Shaped silicon fibre [11].

### 2.2 *Heat extraction modelling*

During operation of the facility the test masses will be subject to continued heating from the laser, viewports, and ambient heat loads within the vacuum as shown in Table 1 [13]. A heat-extraction suspension model was created using finite-element analysis to study heat extraction through thin crystalline fibres of both sapphire and silicon. This study showed steady-state operation to be possible at either 123 K or 18 K with use of heat shields or thermal links respectively. At 18 K heat extraction on the quasi-monolithic stage is entirely through conduction of the crystalline fibres, with no heat links attached to the test masses [13].

| **Heat Source** | **Symbol** | **Value** [mW] |
|---|---|---|
| laser | $P_{\text{laser}}$ | 2 |
| viewport | $P_{\text{viewport}}$ | 14 |
| ambient | $P_{\text{ambient}}$ | 0.1 |

Table 1: Considered cryostat heat loads.

## 3 Current Experimental Projects

### 3.1 *Crystalline Fibre Development*

The production and characterisation of silicon and sapphire crystalline fibres are being investigated, both for use in the GCIF and next-generation detectors. Silicon fibres produced by IKZ Berlin are being characterised through measurements of tensile stress, X-ray diffraction, thermal conductivity, and mechanical loss. These fibres have been produced in float zone furnaces, with fibre shaping and welding demonstrated [11]. Sapphire fibres of a 35 cm length, 1 mm diameter have been grown at the University of Glasgow using a laser heated pedestal growth method [14]. The welding of sapphire fibres is also being explored. More than 75 sapphire-sapphire welds having been demonstrated in the last year with diameters ranging from 0.43 − 1.6 mm, with the ability to repair and re-weld repeatedly. The sapphire fibres and welds have shown promising results for tensile strength, thermal conductivity, crystallography, and mechanical loss [10, 15].

### 3.2 *Blade Spring Design*

Analytical modelling of blade springs has shown that the usual solution of a massless blade spring transfer function (which decreases with frequency ($f$) as $1/\sqrt{f}$ above the blade spring resonant frequency) is not suitable for use in the GCIF. In a realistic case (considering mass of the spring) we consider the blade internal mode, and the difference between the centre of percussion and the load's attachment point on the blade [16]. Blade springs of the optimised geometries have been manufactured from stainless steel, titanium, and beryllium copper, and will undergo measurements of strength, deflection, Q-factor, and mode frequencies at cryogenic temperatures.

### *3.3 Cryogenic Shadow Sensor*

A cryogenic shadow sensor is being developed for local control of the test chain suspension. This design requires balancing several competing elements, aiming for a shot noise limited sensor with a high sensitivity and high dynamic range, while minimising the heat load on the cryostat system.

## 4 Conclusion

This work discusses the design concept of a low-noise crystalline suspension for use as the GCIF cryogenic test cavity optics. This suspension will feature a quasi-monolithic lower stage with silicon test masses and crystalline fibres. This meets the seismic isolation and thermal noise requirements required for a direct measurement of coating thermal noise, and can maintain a steady test mass temperature of 123 K or 18 K. The ongoing experimental investigations for the GCIF are outlined, including crystalline fibre characterisation, blade spring design, and development of a cryogenic shadow sensor.

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