A superconducting inertial sensor for cryogenic gravitational wave detectors

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Sensor development came out of desire to decouple motions
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Previous development at room temperature version
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J.V. van Heijningen et al., 2018, *IEEE SAS proc.*, pp 76-80

Slide courtesy of Joris van Heijningen
Final result of the room temperature inertial sensor

Measurement done on bench MultiSAS prototype at Nikhef.

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Thermal noise not reached, but low Q expected due to (coil-magnet) actuator.

An 8 fm/√Hz sensitivity above 30 Hz, but higher than goal.

Need low-loss actuators and better proof mass residual motion suppression.
Interferometric readout with polarizing optics and Rasnik long range readout
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Old interferometric readout

New interferometric readout

All light ends up at PDs, so 42% less shot noise at same input power and less heat load.
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M. Beker+, 2019, JINST 14 P08010

Old interferometric readout

Frame 15cm
Change of the actuator to access low frequency sensitivity

- Q-factor limited by eddy currents induced by the actuator magnet in close proximity to moving metal parts.
- Niobium is a superconductor below $T_c \cong 9.2$ K and in the full Meissner state below 5 K.
Determining the force of the actuator on the proof mass
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Magnetic pressure on proof mass by Meissner effect

Finite element simulations matches analytic calculations
Determining the force of the actuator on the proof mass

- For one point: \( B_z \propto \frac{I \times N}{z^2} \) and \( F_z \propto B_z^2 \)
- \( z \) is limited by practical (physical) configuration

- \( I \) is limited by the cryo-chip controller
- \( N \) is limited by masking technique for depositions
Building the superconducting thin film
Building the superconducting thin film

Collaboration with Innovative Coating Solutions (Belgium) for custom superconducting coils.

Superconductivity collaboration and testing with Andrea Perali (UniCam) and Filip Tavernier (KULeuven), respectively.

Choosing right mask manufacturing technique.

Now (magetron) sputtering Nb and NbN

Pitch precision for the mask: about 100 µm.
A Cryogenic Superconducting Inertial Sensor (CSIS)

J.V. van Heijningen, 2020, *JINST* 15 P06034

M. Beker+, 2019, *JINST* 14 P08010
Comparison to the state-of-the-art
A frame (in 2 pieces) and proof mass is cut out of highly doped silicon block using spark erosion machining (EDM).

The leg and flexures are laser assisted plasma etched out of a thick 500 μm high-quality wafer.

HCB ≡ Hydro-Catalysis Bonding
Where can we test these cryogenic, fm/√Hz class inertial sensors?

We need to create a cold environment that moves only a factor 100-1000 more than or seismometer sensitivity goal.
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We need to create a cold environment that moves only a factor 100-1000 more than or seismometer sensitivity goal.

Another option would be to deploy them in the E-TEST ([https://www.etest-emr.eu](https://www.etest-emr.eu)) prototype.
Using the moon as a gravitational wave detector
Using the moon as a gravitational wave detector
Using the moon as a gravitational wave detector
Summary

• Cryogenic inertial sensor with fm/VHz displacement sensitivity from 0.5 Hz onward;

• Changes include: superconducting, low-noise actuators, polarized interferometric readout and Rasnik readout;

• This sensor can be deployed in the natural cryostats on the Lunar pole craters; a cryogenic sensor array can directly detect the effects of GWs on the Moon;

• The inertial sensor is a first application test for the actuators and in future we will look at applications as in the cryogenic suspension chain.
Bonus and backup slides
A detailed noise budget of CSIS-Si and Nb thermal noise
Polarizing optics divert all the available power onto the photodiodes, avoiding dumping part of it. This is a important feature when working at cryogenic temperatures and it also means less shot noise for given injected power. Indeed, in Tab. 1 we can compare the powers received by the photodiodes and the overall shot noise when polarizing and non-polarizing optics are used. The total shot noise expected in the interferometer output depends on the amount of power falling on the photodiodes as $SN_i \propto 1/\sqrt{P_i}$. The total shot noise is then $SN_{tot} = \sqrt{SN_{PD_1}^2 + SN_{PD_2}^2}$.

Table 1. Comparison of interferometric readout outputs and shot noise without and with polarizing optics for a given input power $P_0$.

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Power on PD1</th>
<th>Power on PD2</th>
<th>$SN_{tot}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>previous configuration$^{12}$</td>
<td>$P_0/4$</td>
<td>$P_0/8$</td>
<td>$\propto \sqrt{12}/P_0$</td>
</tr>
<tr>
<td>with polarizing optics</td>
<td>$P_0/2$</td>
<td>$P_0/2$</td>
<td>$\propto \sqrt{4}/P_0$</td>
</tr>
</tbody>
</table>

We thus get a factor $\sqrt{3}$ of reduction in the shot noise when polarizing optics are employed with respect to the non-polarizing optics case.
Other possible application:

LGWA: a bridge towards lower frequencies

- New possible discoveries
- Binary Neutron Stars & Double White Dwarf: Hours → Parameter estimation, EM early warning, Sky localization with only LGWA.
- Polarization measurements and tests of gravity theories.
Figure 1. Simplified GW response model (red) used in this paper, with normal-mode sum truncated at $n = 22$. The response curve of a pessimistic response model is shown in gray for comparison. The models only include spheroidal quadrupole modes.
Figure 5. Diffractogram of (a) niobium film with theoretical value (dotted lines) and (b) niobium nitride film with theoretical values for \(\delta\) and \(\epsilon\) phases (dotted lines).
Dimensions

10 turns

w = 225 µm
225 µm

20 turns

w = 112.5 µm
112.5 µm

30 turns

w = 75 µm
Increasing the actuator’s hole size

15mm diameter for the outside hole, 14mm closer to the proof mass

The suspension points were shifted.
How much more sensitive is this cold inertial sensor?

- T = 290 K, Q = 150, viscous
- T = 5 K, Q = 10^4, structural
- T = 5 K, Q = 10^6, structural
- Interferometric readout noise

Slide courtesy by Joris van Heijningen

How much more sensitive is this cold inertial sensor?

Slide courtesy by Joris van Heijningen

S. Hild et al., Class. Quant. Grav. 27 015003 (2010)
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Slide courtesy by Joris van Heijningen
Using superconductivity in the readout: a SQUID

Slide courtesy by Joris van Heijningen
Room temperature sensor