

A Superconducting Resonant LC Displacement Sensor using a Digital Phase-Locked Loop

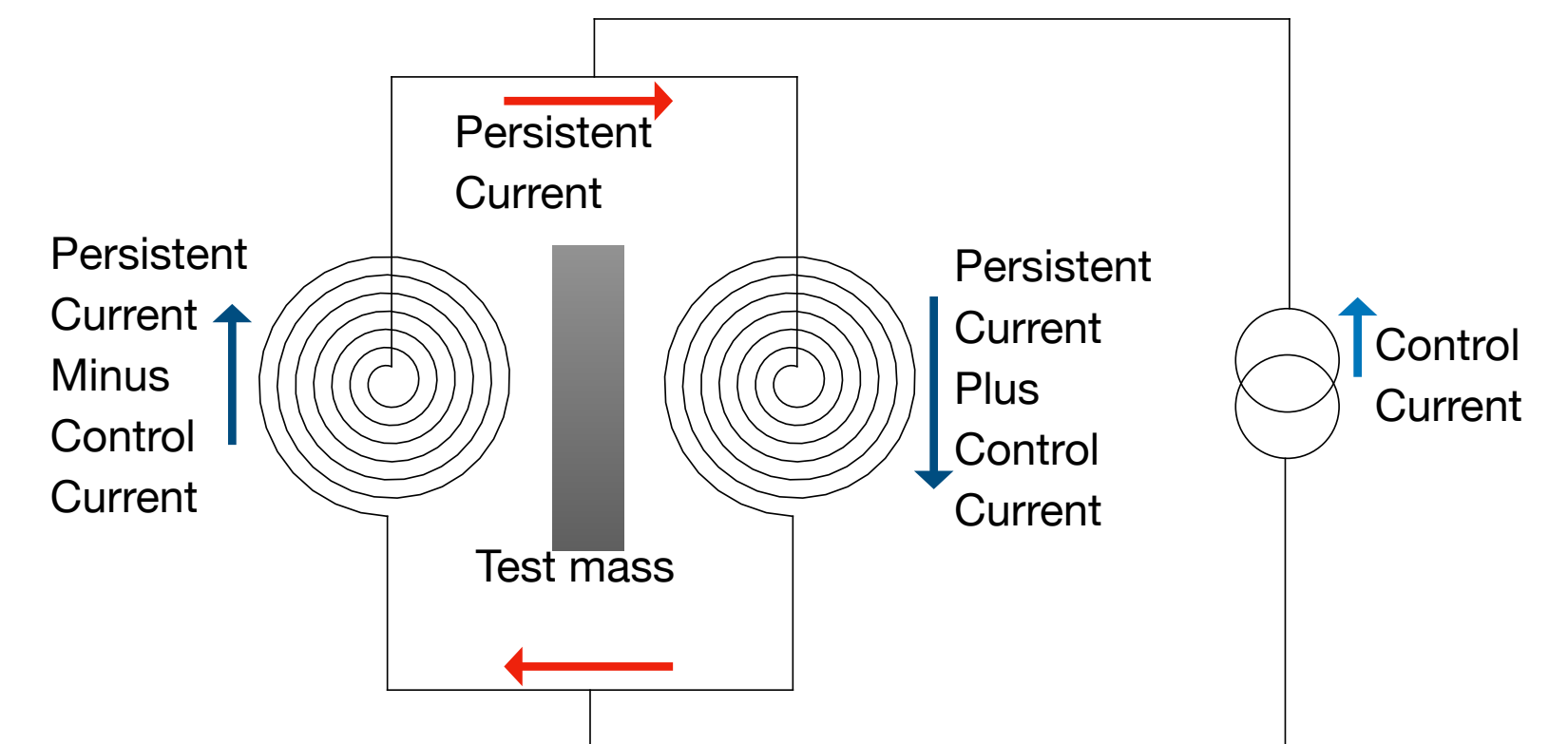
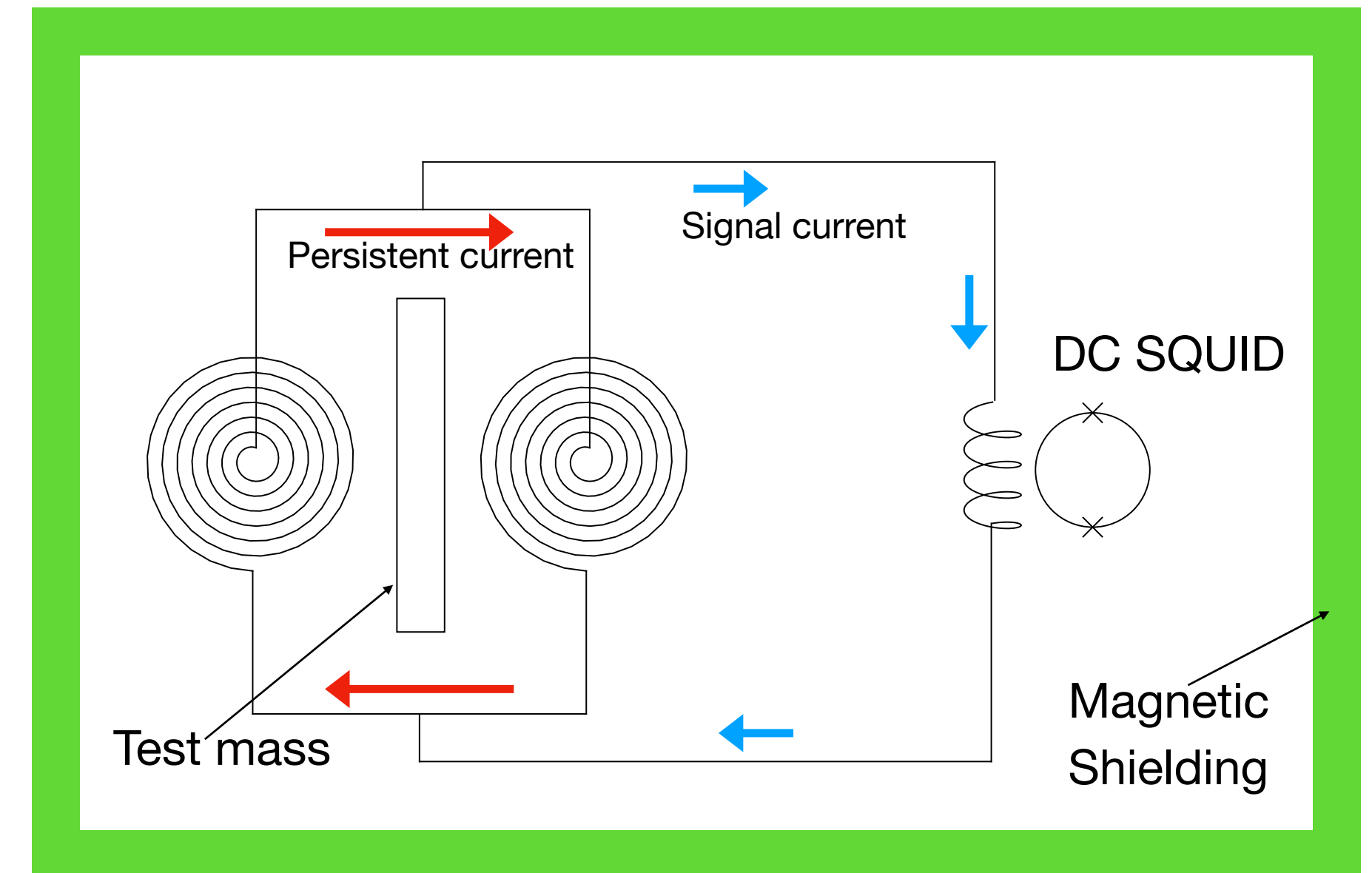
Christopher Collins, Veerle Ellenbroek, Joris van Heijningen (Nikhef)
LGWA, 30th September 2026

Outline of talk

- Current design status
- Challenges with NbN
- Alternative actuation scheme
- Alternative sensing schemes

Sensor and actuators: current design status

- Persistent current inductive displacement sensor with DC SQUID offers sub-fm.Hz^{-1/2} sensitivity, with a simple compact circuit.
- Actuator circuit - nN forces, force noise minimised by using large noise-free persistent current, smaller control current.
- Detailed FEM and analytic models of coils developed at Nikhef.
- NbN coils have been fabricated with thickness up to >500 μm , demonstrated $T_c > 15\text{ K}$ and $I_c > 300\text{ mA}$



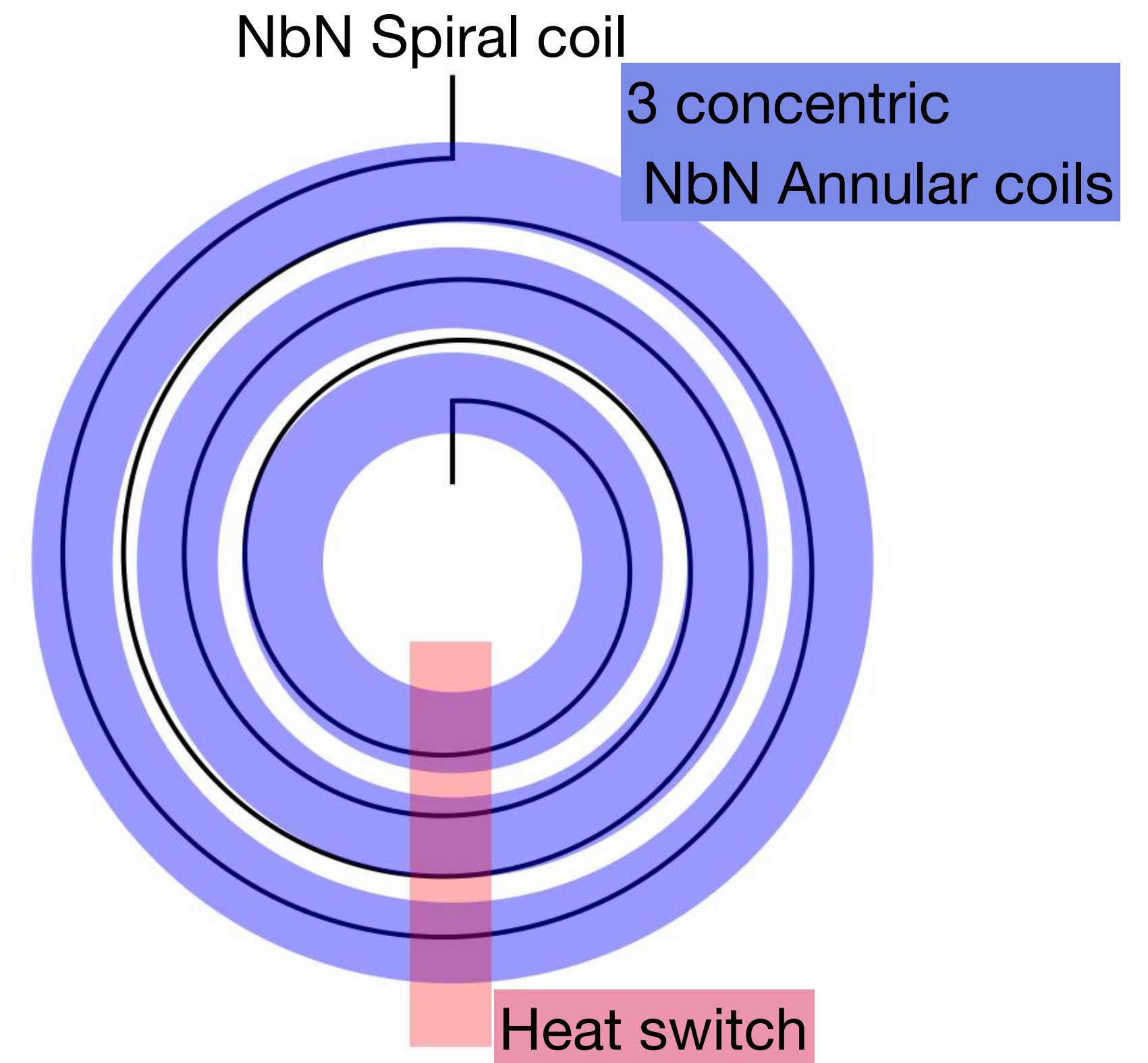
Challenges with present design

- Can NbN can store persistent current indefinitely? or for long enough?
- Interconnections between circuit elements
 - yet to be developed
 - can they carry persistent current?
- Small size -> small inductance of coils
- NbN or other high temperature SQUID must be developed.

Potential design modifications to mitigate risks

1. Modified actuator coil

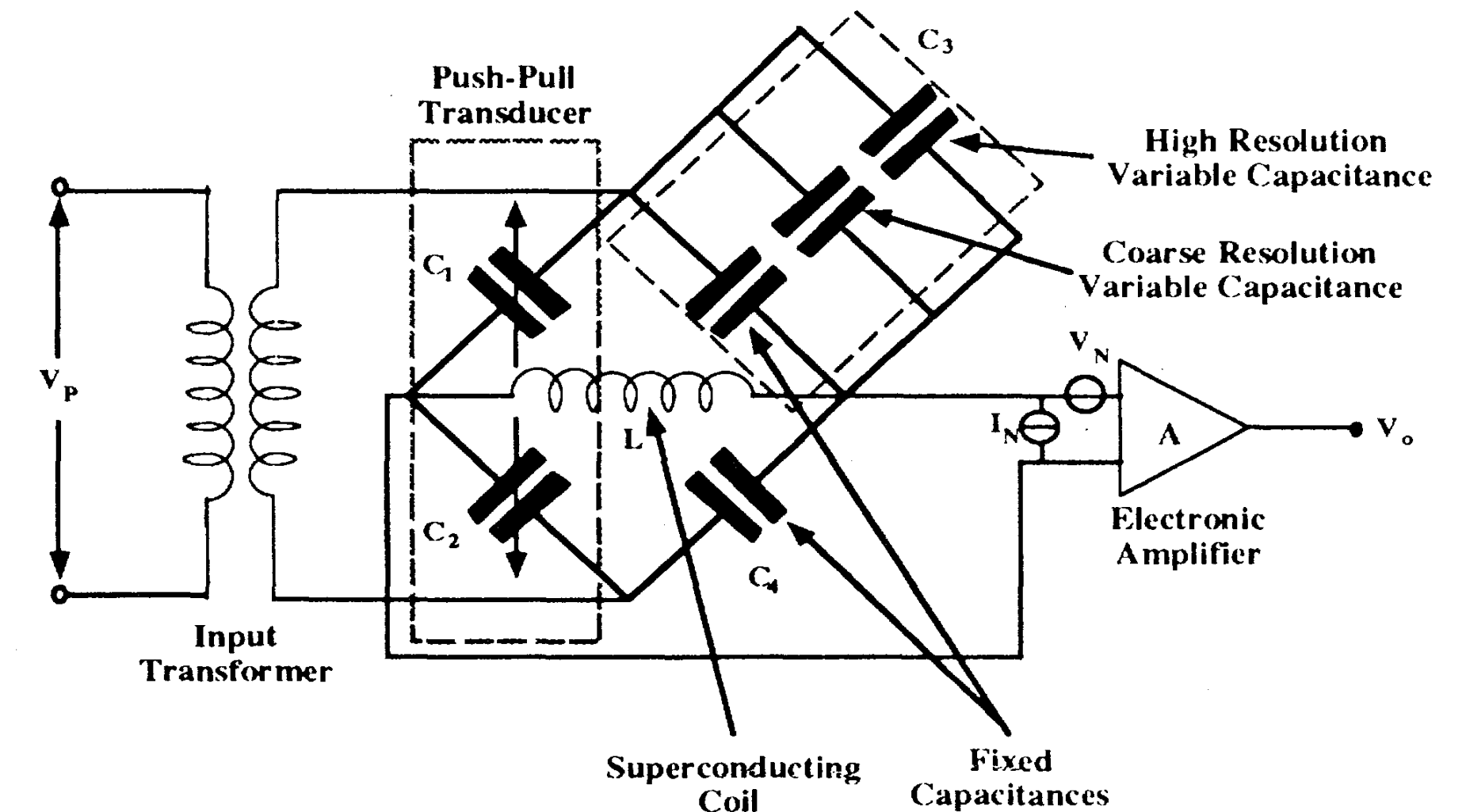
- Actuator coil replaced by concentric rings.
- Spiral coil inductively couples to rings. Only the rings store persistent current.
- Smaller control current superposed on larger persistent current through inductive coupling.



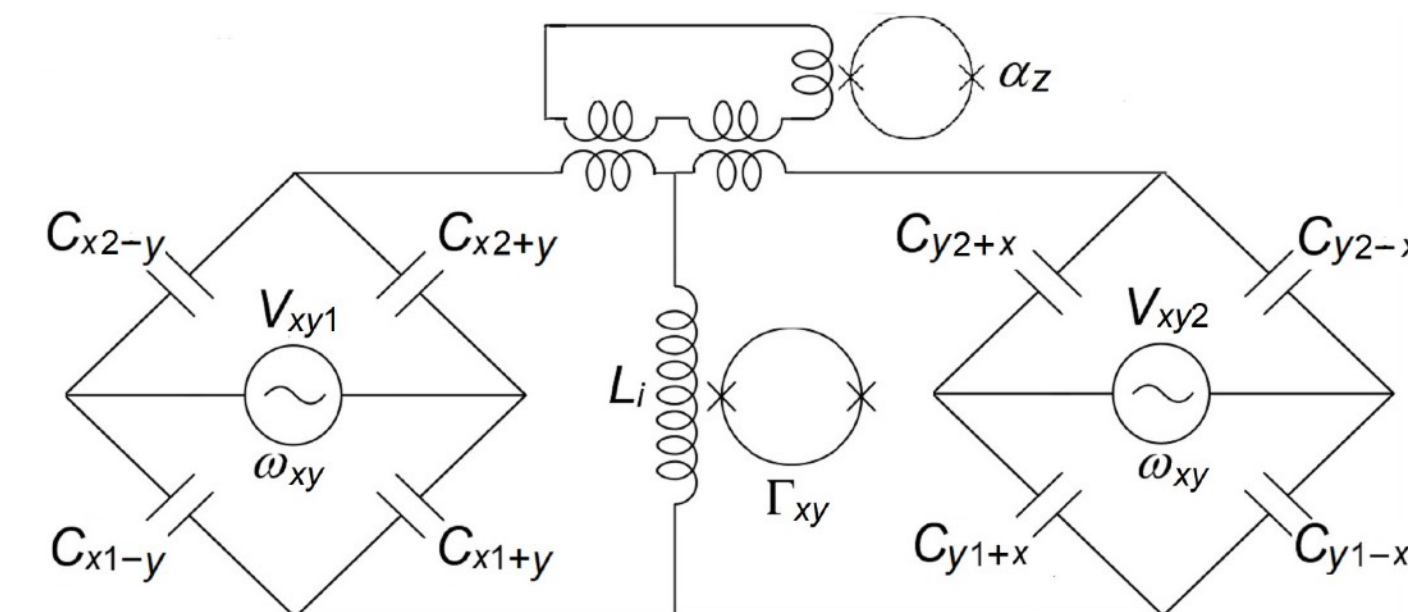
2. Alternative sensing circuits

2.1. Superconducting resonant LC Bridge sensor

- Established technology, used in resonant bar GW detectors.
- Proposed for use in gravity gradiometers and decihertz GW detectors.
- Resonant LC circuit cancels imaginary impedance
- Bridge circuit nulls signal at equilibrium point, allowing large amplification of signal by SQUID
- Target Q of LC circuit = 10^6 . Large Q $\rightarrow$ Large displacement signal
- Recently observed Q of $2 \cdot 10^6$ at 250 kHz (SQUID Readout of a High-Q Superconducting LC Resonator, Roman Kolevato, Saptarshi Chaudhuri, and Lyman Page, arXiv:2607.20831)
- LC circuits at 1 - 5 MHz used for Athena SC pixels

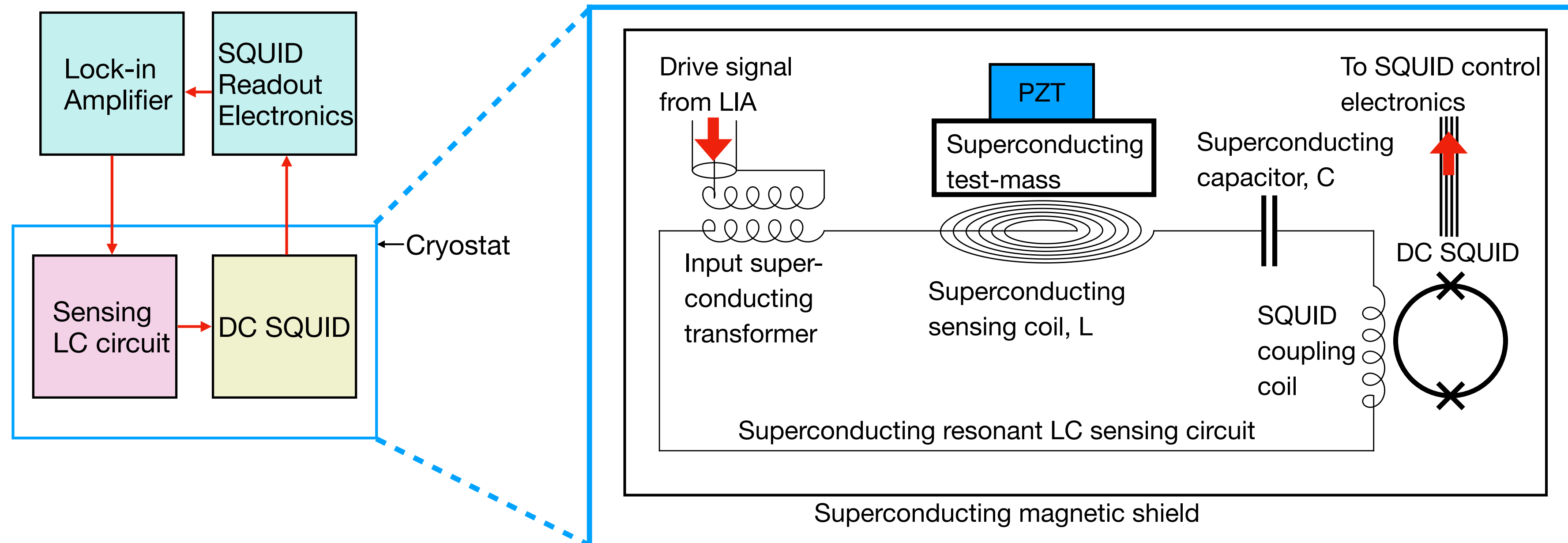


Back-action-evading transducing scheme for cryogenic gravitational wave antennas, C. Cinquegrana, E. Majorana, P. Rapagnani and F. Ricci, PHYSICAL REVIEW D VOLUME 48, NUMBER 2 (1993)



SOGRO (Superconducting Omni-directional Gravitational Radiation Observatory); Ho Jung Paik; EPJ Web Conf. Volume 168, 2018 Joint International Conference of ICGAC-XIII and IK-15 on Gravitation, Astrophysics and Cosmology

2.2. Resonant SC LC circuit with Phase-Locked Loop



- Resonant frequency of superconducting LC circuit is tracked, and the drive frequency of digital lock-in adjusted to stay on resonance.
- Amplitude is then (almost) constant - displacement signal given by resonant frequency.
- Gradient of feedback signal for control system then proportional to electrical Q of circuit.
- Resonant frequency depends only on superconducting circuit - insensitive to input cables.

Projected sensitivity

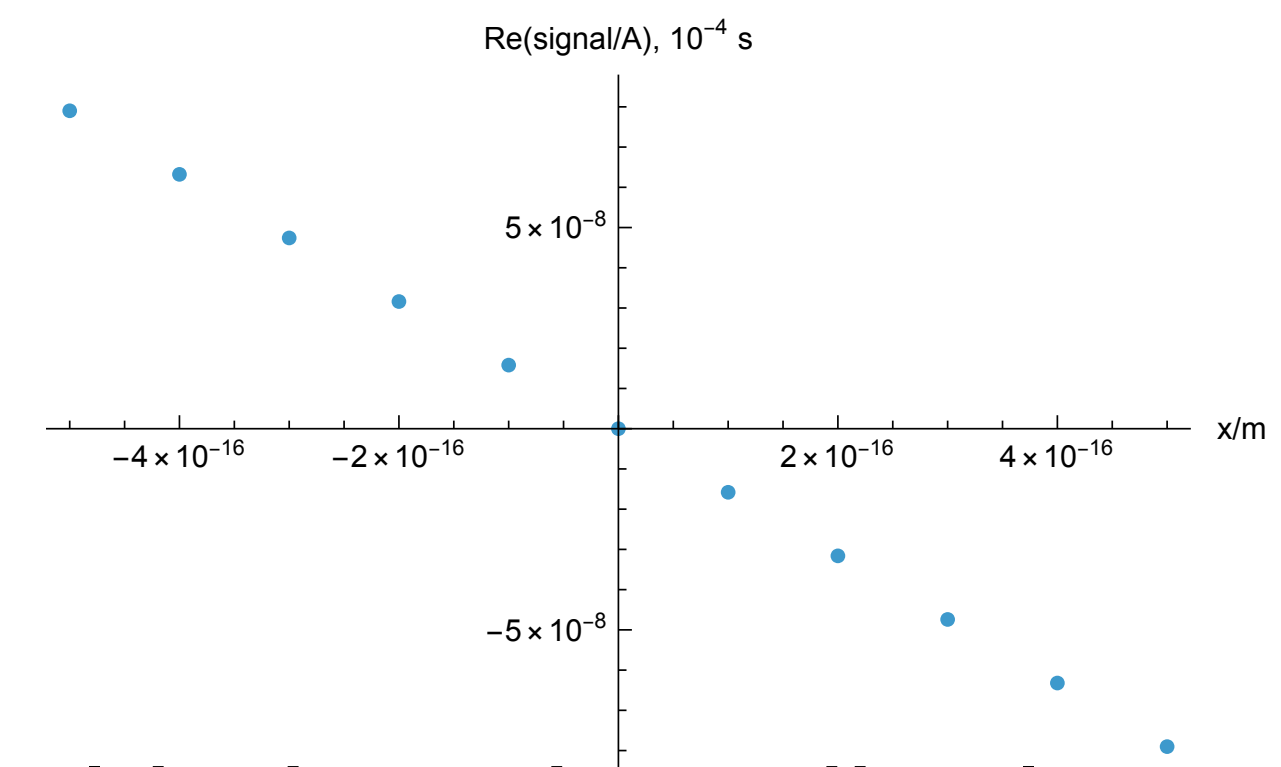
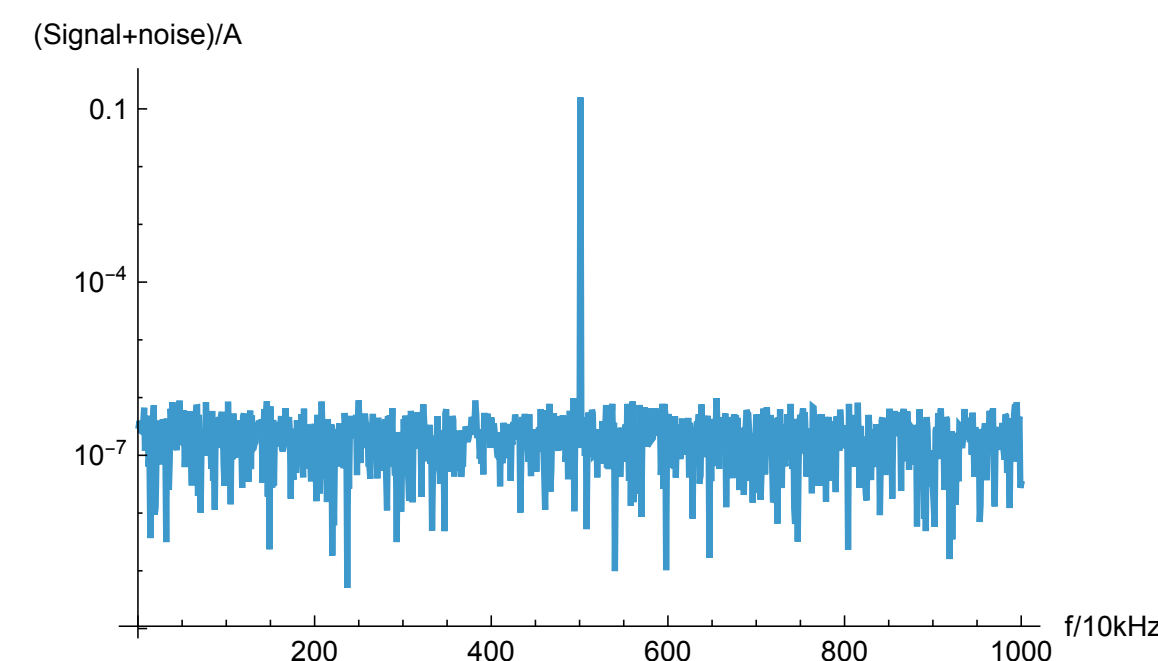
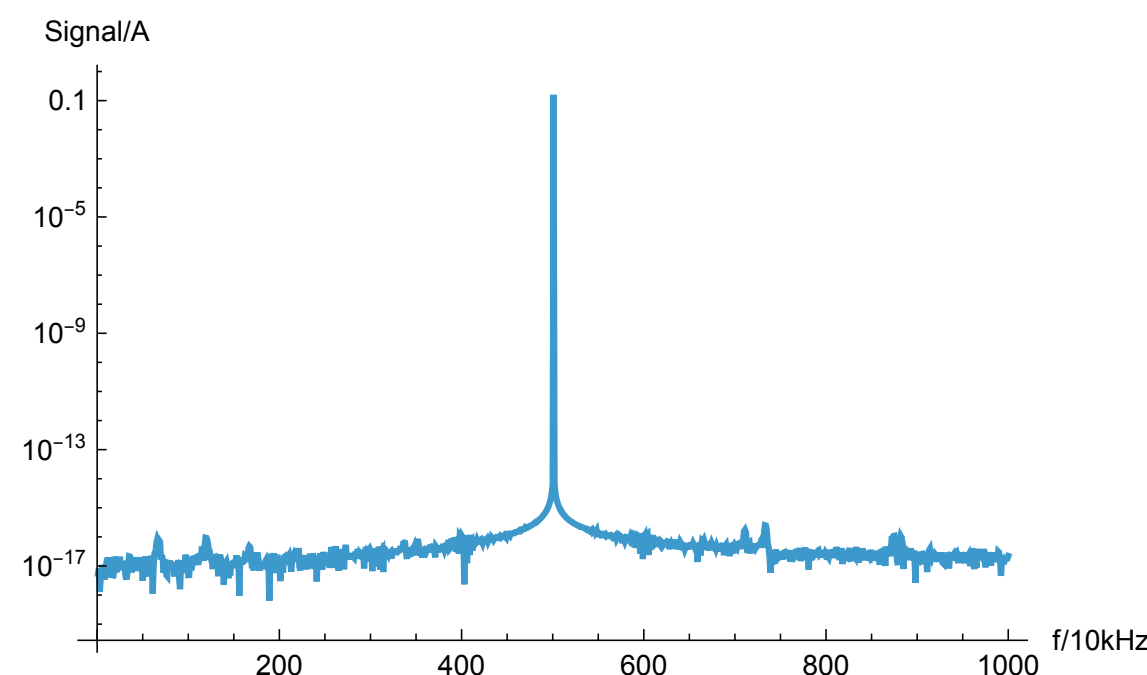
- Persistent current sensor: current per displacement, current sensitivity of DC SQUID

$$\sqrt{S_x} \approx \sqrt{S_I} \frac{dx}{dI_{sq}} \approx \frac{\sqrt{S_I} gap}{I_{pers}} \approx 10^{-15} m Hz^{-1/2} \frac{gap}{10^{-3} m} \frac{1 A}{I_{pers}} \frac{\sqrt{S_I}}{10^{-12} A Hz^{-1/2}}$$

- LC phase-locked loop sensor: phase per displacement, phase sensitivity of LIA

$$\sqrt{S_x} \approx \frac{dx}{d\phi} \sqrt{S_\phi} \approx 5 \times 10^{-17} m Hz^{-1/2} \times \frac{gap}{10^{-3} m} \frac{10^6}{Q} \frac{3 MHz}{f_{drive}}$$

- Simulated data including current noise from LIA and input cables gives similar results



FFT of simulated signal (l) and signal + noise (r)

Signal in band vs displacement

Comparison of sensing approaches

Type of superconducting displacement sensor	Persistent Current sensor	LC Bridge sensor	Proposed LC Phase-Locked Loop sensor
Sensitivity	$\sim 10^{-16} \text{ m Hz}^{-1/2}$	$\sim 10^{-16} \text{ m Hz}^{-1/2}$	$\sim 10^{-16} \text{ m Hz}^{-1/2}$
Requires RF Electronics	No	Yes	Yes
Required current	$\sim 1 \text{ A}$	$\sim 1 \text{ A}$	$\sim 1 \text{ mA}$
Range that can be tracked	$\sim \pm 0.2 \text{ mm}$	$\sim \pm 5 \text{ nm}$	$\sim \pm 0.2 \text{ mm}$
1/f noise at low frequency	Yes	No	No
Requires superconducting interconnections	Yes	No	No
Sensitive to stray impedance of cables	No	Yes	No
Multiple sensors can be multiplexed to single SQUID	No	Yes	Yes
Required current sensitivity	$\sim \text{pA}$	$\sim \text{pA}$	$\sim 100 \text{ pA}$
Has been experimentally demonstrated and used	Yes	Yes	Underway!

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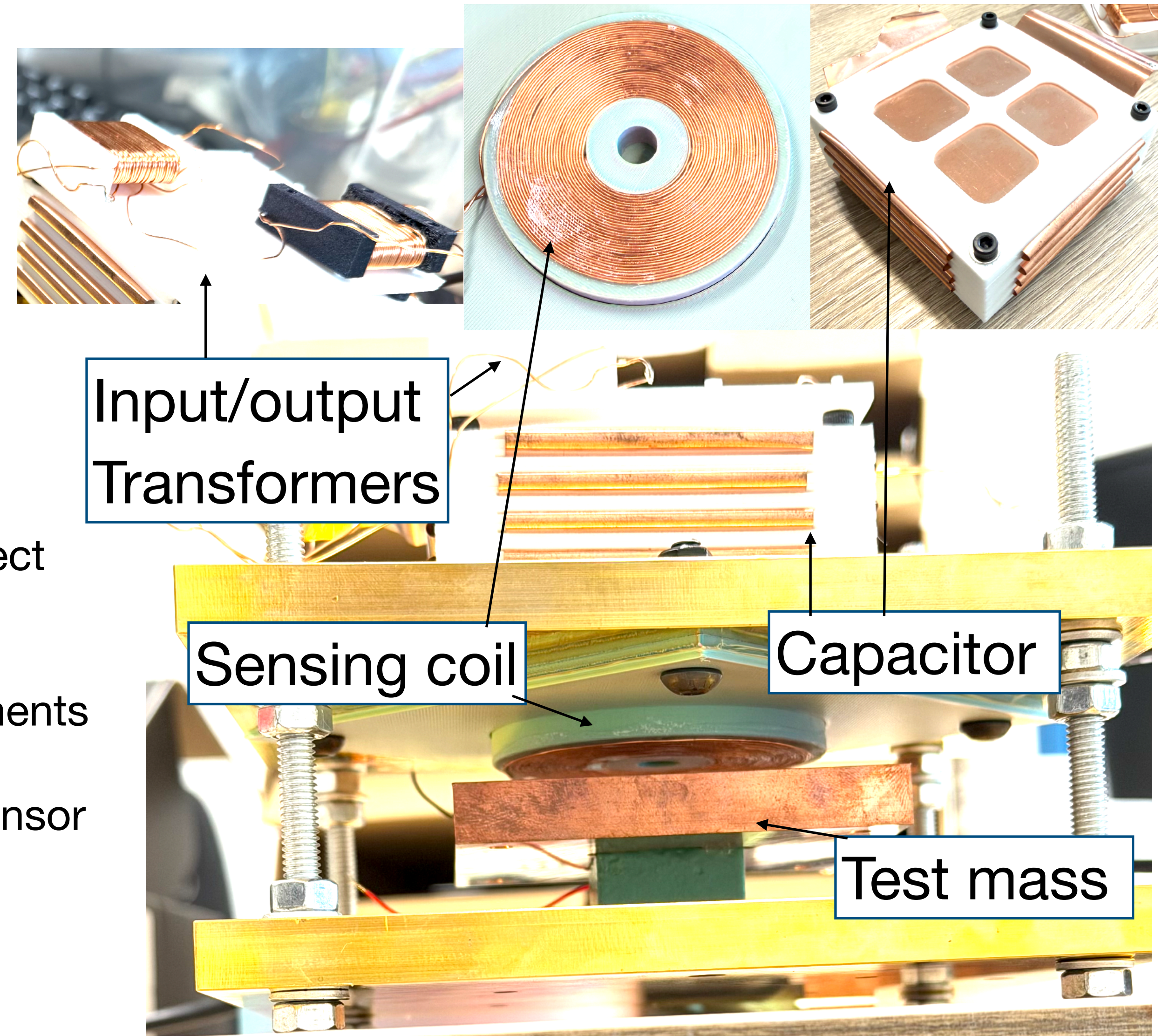
Underway!

Current status of SC LC PLL sensor

- We have funding for components, currently ordering digital LIA (MokuPro), SQUIDs (Magnicon 2-stage DC SQUIDs), Nb shielding and wires, magnetometer, spot-welder, cryo-coax. Cables, etc.
- Initial tests to use combination of Nb and NbN components (eg magnetic shielding, initial DC SQUIDs, would be Nb).
- NbN coils already exist, NbN capacitors to be manufactured
- First SC capacitors to use dielectric; can be replaced by vacuum if necessary to improve Q
- To be tested at low-vibration cryogenic facility at Nikhef, sub 10K in 30 minutes, sub-fm.Hz^{-1/2} from 10 Hz+

Development of room temperature analog of SC LC PLL sensor

- Same principle should work at room temperature
- Likely limiting factor is the low Q of the LC circuit
- Large coil has large resistance at high frequency
- Can be mitigated by using a large C and small L
- Eddy current screening of B field mimics Meissner Effect at high frequency (skin depth $\sim 80 \text{ } \mu\text{m}$ at 1 MHz)
- Rapid prototyping in progress with 3D printed components
- Could produce useful sub - $\text{pm} \cdot \text{Hz}^{-1/2}$ displacement sensor



Conclusions

- Alternatives exist to persistent current actuation and sensing schemes.
- Actuation control current can be inductively coupled into circular coils.
- LC sensors can avoid need for persistent current interconnections.
- Tracking the resonant frequency of the circuit -> large displacement range, reduces sensitivity to stray impedance and amplitude noise.
- Manufacture and testing of prototype sensors underway at Nikhef