

GRAFIQO (Preventivi 2025)

GRAvitational Force In Quantum Optomechanics

CSN2- Started January 1 2023; 6 years

Objectives: explore the territory between quantum physics and gravity. More specifically

- 1. Measurement of gravitational force produced by the **smallest source mass** (masses ~ 10 mg)**
- 2. Measurement of this small force when the test mass oscillator **is in a quantum state** (limited only by quantum fluctuations)**

Responsabile nazionale: **Francesco Marin**

Unità INFN partecipanti: **Trento, Firenze, Perugia**

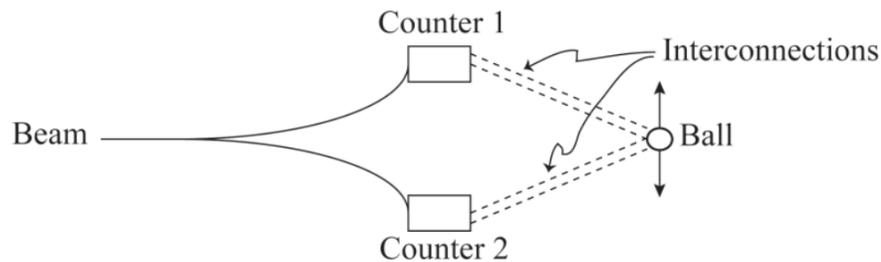
Responsabili locali: **Enrico Serra (TN) , David Vitali (PG)**

PHYSICS & MOTIVATION

Are we sure that gravity must be quantized ?

We can answer even **without any clue on quantum gravity** (i.e. in a model-independent way)

R. Feynman, in Chapel Hill Conference Proceedings (1957)



- Put a source of a gravitational field in a quantum superposition of two separated locations
- Verify its quantum nature by detecting entanglement on a degree of freedom of the source-probe mass system

PRL 119, 240402 (2017)

PHYSICAL REVIEW LETTERS

week ending
15 DECEMBER 2017

Gravitationally Induced Entanglement between Two Massive Particles is Sufficient Evidence of Quantum Effects in Gravity

C. Marletto¹ and V. Vedral^{1,2}

¹Clarendon Laboratory, Department of Physics, University of Oxford, England

²Centre for Quantum Technologies, National University of Singapore, Block S15, 3 Science Drive 2, Singapore

(Received 6 September 2017; published 13 December 2017)

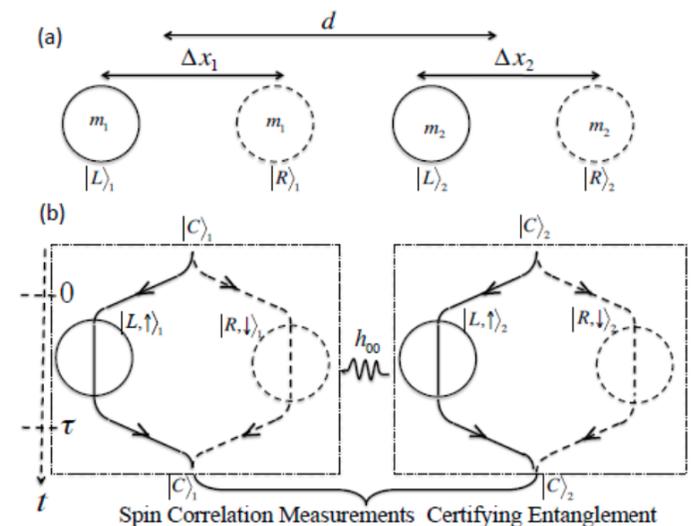
PRL 119, 240401 (2017)

PHYSICAL REVIEW LETTERS

week ending
15 DECEMBER 2017

Spin Entanglement Witness for Quantum Gravity

Sougato Bose,¹ Anupam Mazumdar,² Gavin W. Morley,³ Hendrik Ulbricht,⁴ Marko Toroš,⁴ Mauro Paternostro,⁵ Andrew A. Geraci,⁶ Peter F. Barker,¹ M. S. Kim,⁷ and Gerard Milburn^{7,8}

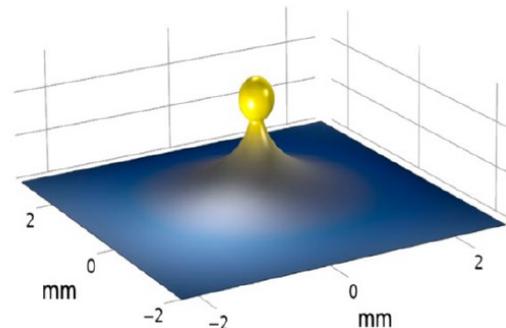
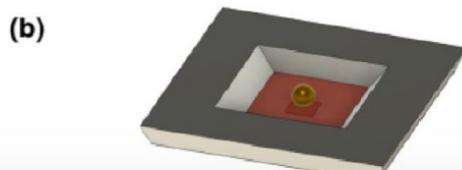
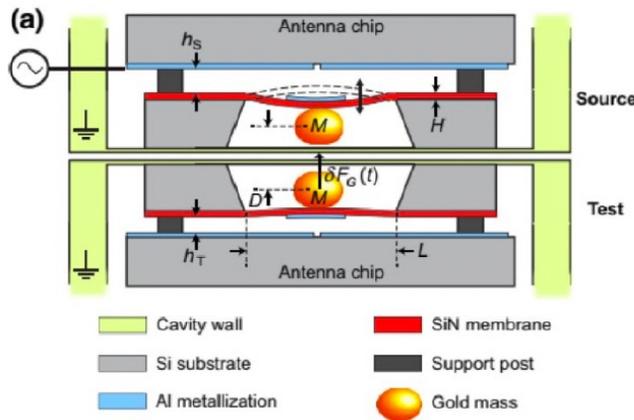


These proposals are too hard in view of current technology

one needs to keep large enough masses isolated from noise and decoherence for a long enough time t

$$\varphi_g \approx \frac{\Delta E_{grav} t}{\hbar} \approx G \frac{m_s m_p}{\hbar d} t$$

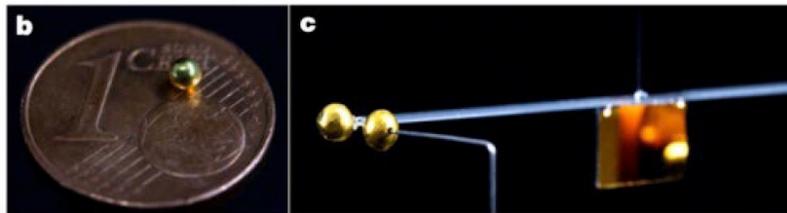
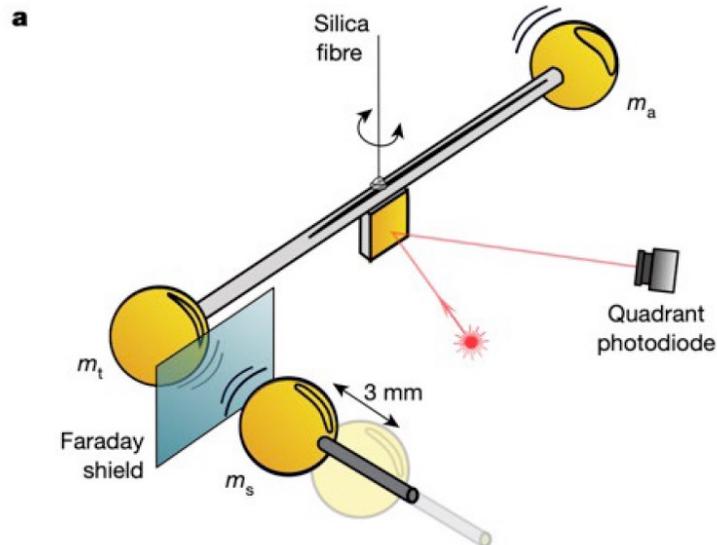
We target a fundamental **intermediate** step: **accurate measurement of the gravitational force between objects in a quantum state**, i.e., with quantum-limited position-momentum fluctuations



For example:
Masses are operated and measured by coupling to microwave cavities in a dilution cryostat at 10 mK (M. Sillanpää, Phys. Rev. Applied **15**, 034004 (2021))

Scientific state-of-the-art

A recent experiment that revealed the gravitational force in case of **sub-100 mg masses (in the classical regime)**



Torsional pendulum
(interaction between two gold spheres)

Test mass (mg)	90.7
Source mass (mg)	92.1
Quality factor	4.9
Resonance frequency (Hz)	3.59×10^{-3}
Modulation frequency (Hz)	12.3×10^{-3}
Temperature (K)	300
Vacuum (Pa)	6×10^{-7}

Aspelmeyer Group in Vienna
Nature 591, 225–228 (2021)

Quasi-resonant measurement of a
modulated gravitational force

$$F_{\text{mod}} = \frac{\partial F_g}{\partial x} A_{\text{mod}} \quad F_g \approx G \frac{m_s m_p}{x^2}$$

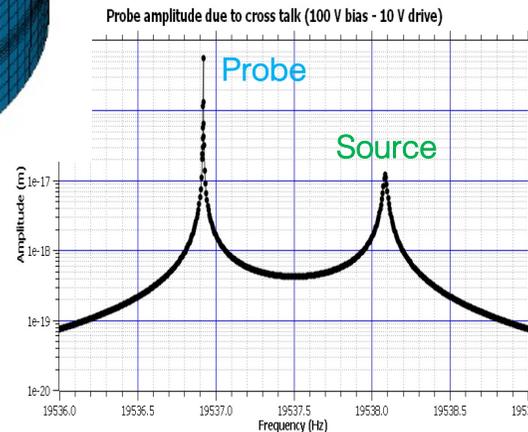
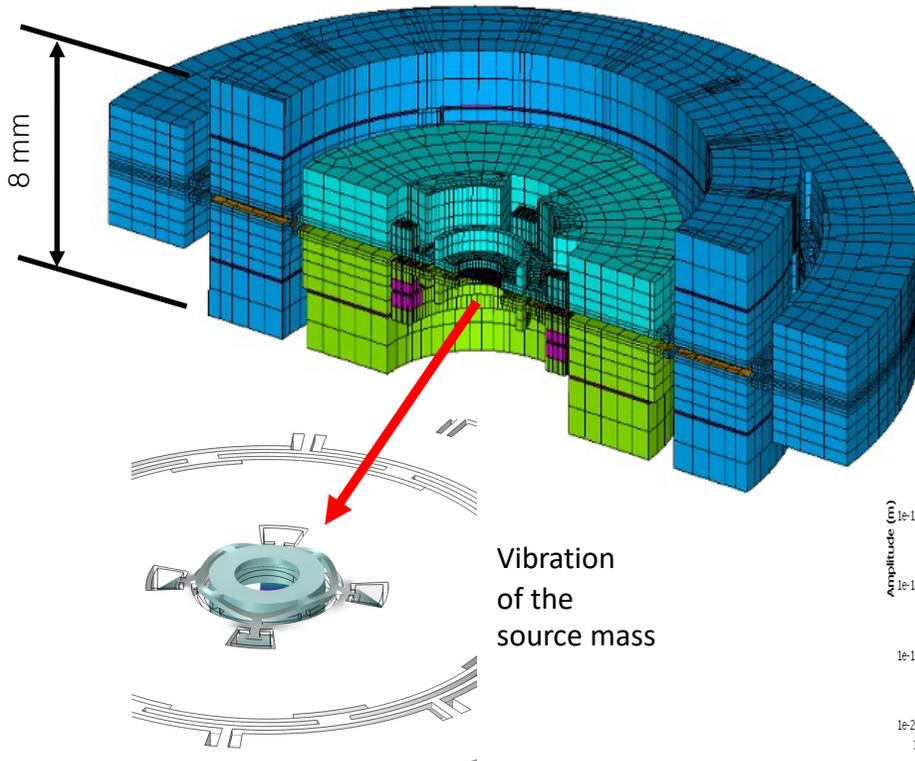
Source-Probe design (CDR)

Resonant measurement of the gravitational force between two mass Silicon "disk" resonators; the probe mass is optically read via radiation pressure on a SiN membrane

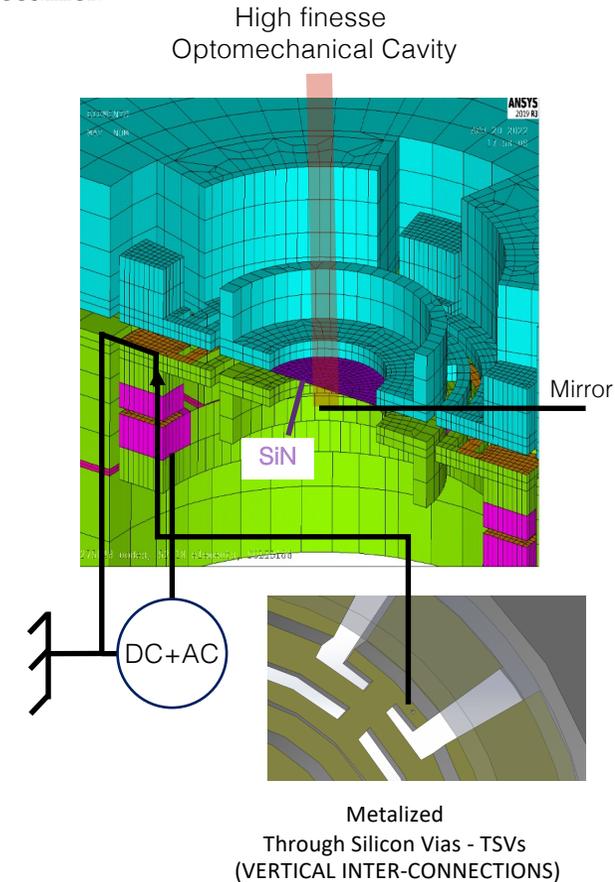
Caratteristiche richieste per gli oscillatori

- *Probe*: alto fattore di qualità meccanico (Q).
- *Source*: elevata ampiezza di oscillazione (1-10 μm).
- Assenza di cross-talk diretto: schermo elettrostatico + filtri meccanici.

	<i>Source</i>	<i>Probe</i>
massa sensibile (mg)	m_g	14.9 ^a
massa efficace (mg)	m_{eff}	37 ^b
fattore di qualità	Q	50×10^6 ^d
frequenza di risonanza (kHz)	$\Omega/2\pi$	20
temperatura (K)	T	0.02



WP1 - CDR

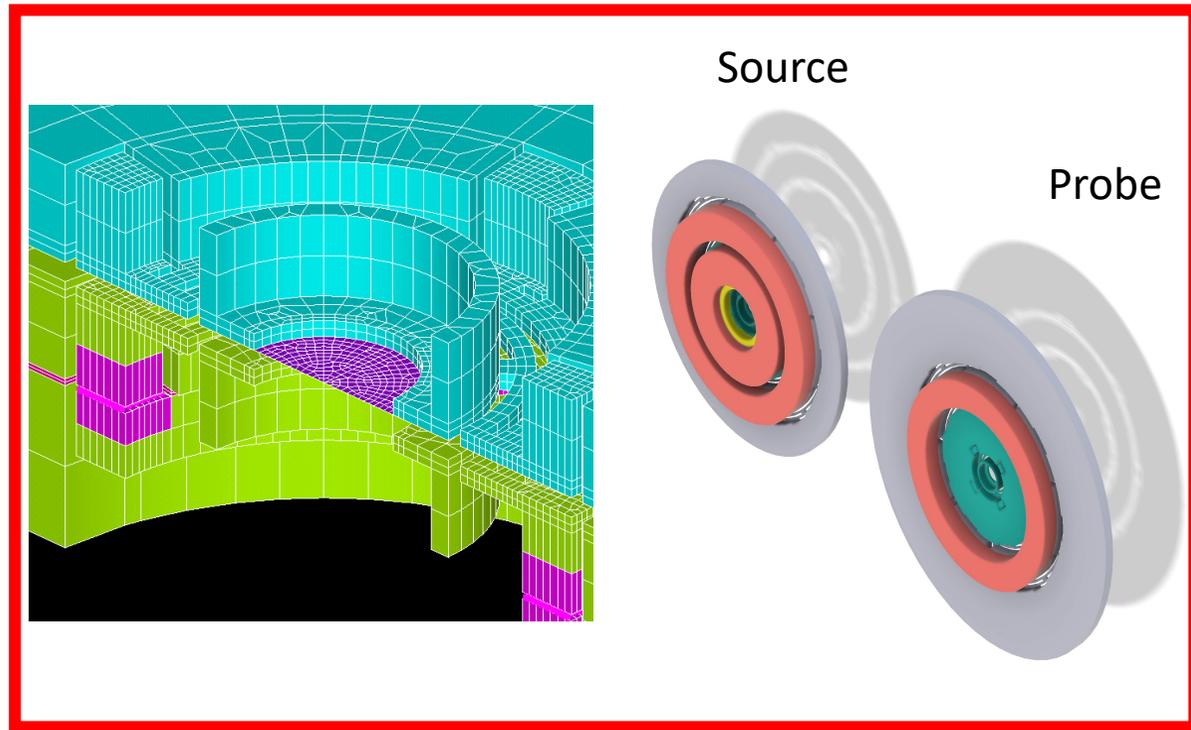
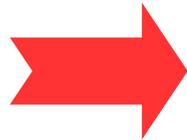
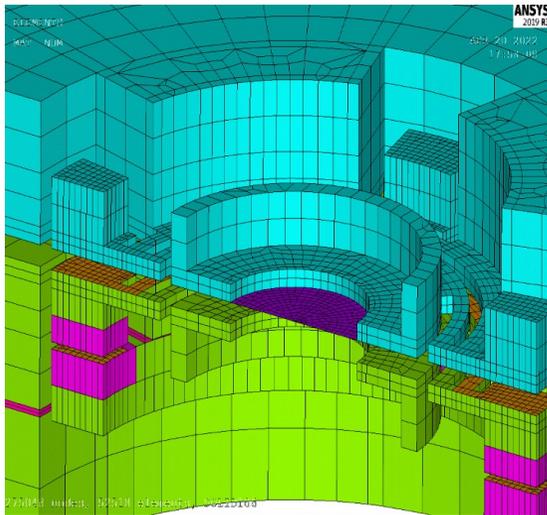


Source-Probe redesign (2023-2024)

WP1 - CDR

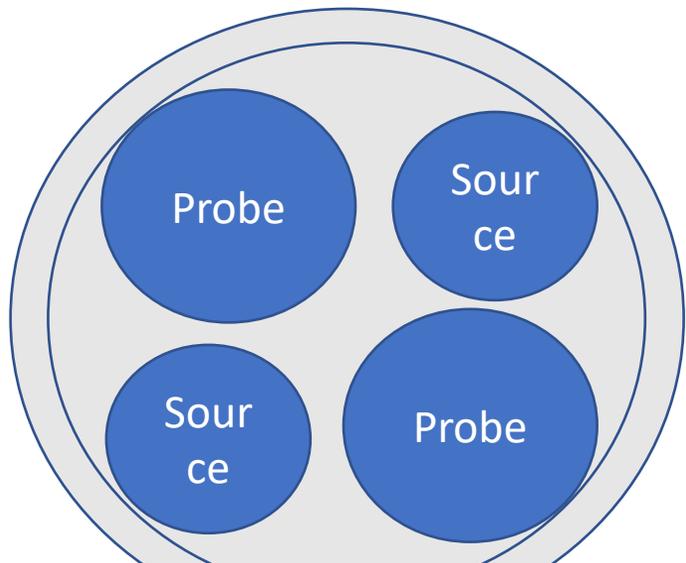
After the evaluations with the potential producer of the silicon oscillators, we made an initial round of modifications to the structures to meet the constraints imposed by the machinery used.

- Reduced the overall thickness from 2000 to 1500 microns and avoided RIE etching with double depth.
- Repeated all FEM simulations and verified that the current design maintains the performance and critical aspects of the original proposal.

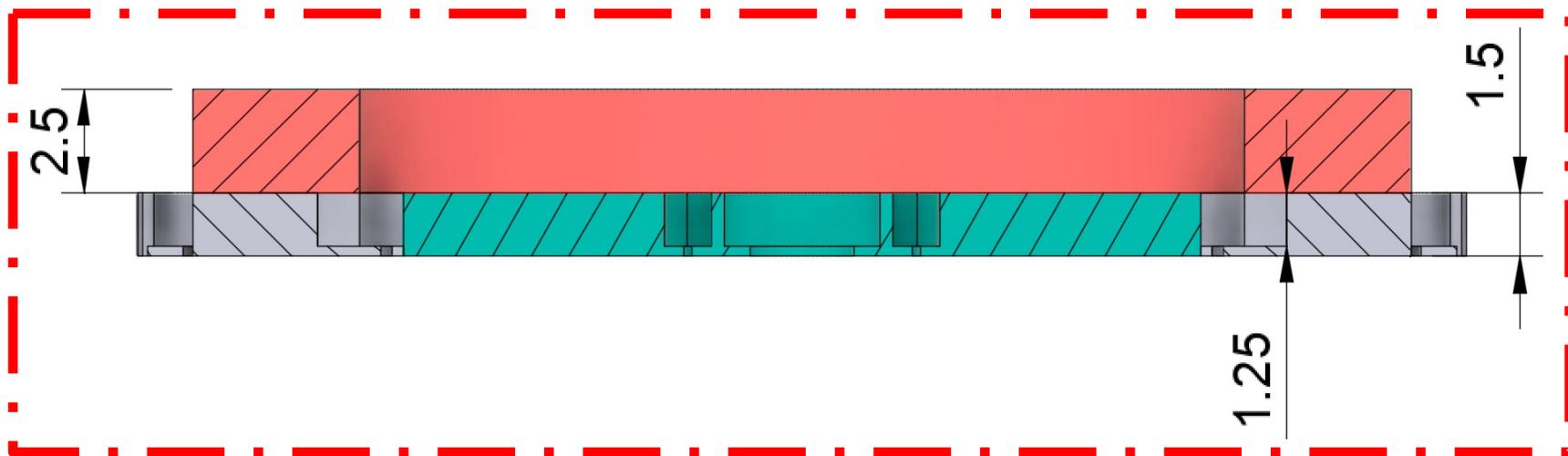
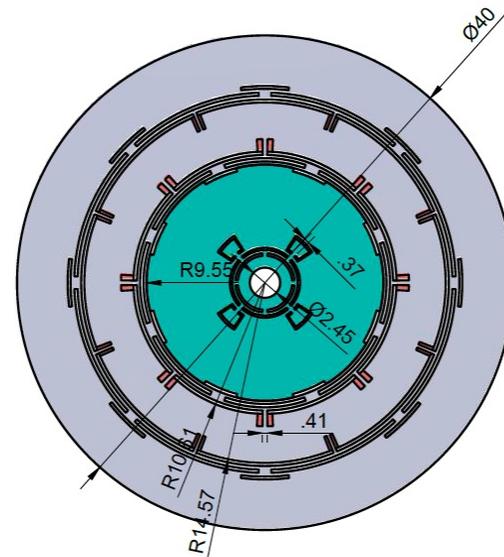
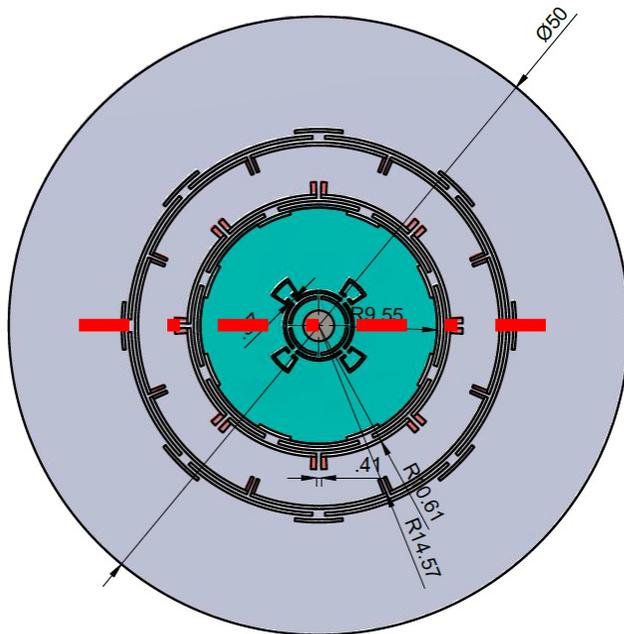


Source-Probe frequency uniformity (2024)

WP1 - CDR



6-inch wafer

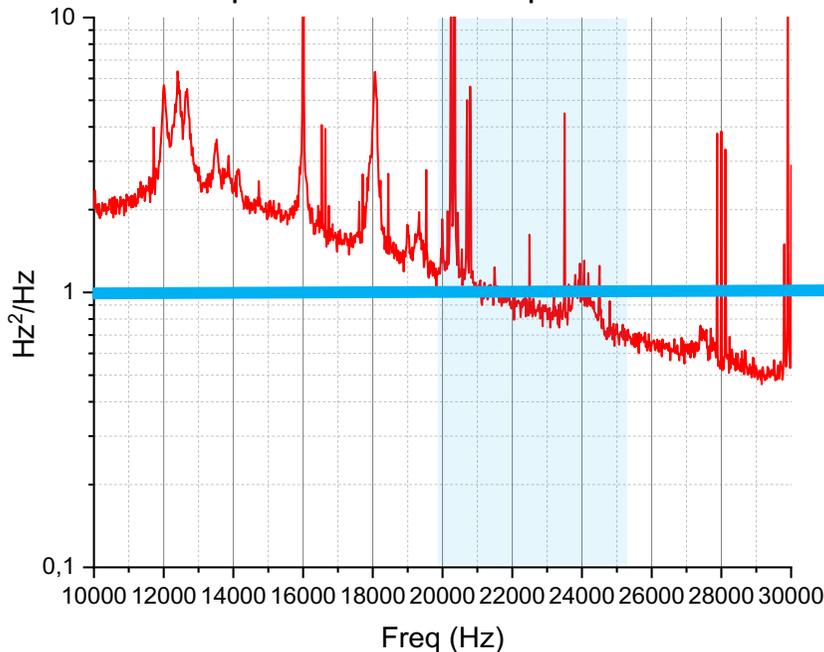


Cavity design 2023- 2024-2025

a) Lunghezza di cavità 11 mm, cavità priva di PZT. E' la configurazione attualmente in uso a Camerino. La lunghezza di cavità consente di raggiungere la condizione di risonanza tra laser e cavità agendo unicamente sulla frequenza del laser (accordabile su ca 30 GHz). Non è possibile ottimizzare l'accoppiamento tra membrana e campo in cavità, che rimane quindi casuale. L'accoppiamento ha circa 2/3 di probabilità di risultare entro un fattore 2 dal massimo (livello che consideriamo accettabile). Nel caso risultasse troppo basso, è necessario smontare la cavità e riprovare, variando leggermente le distanze.

b) Lunghezza di cavità 3 mm, con specchio di ingresso e schermo (comprendente lo specchio posteriore) montati su PZT. Il primo PZT permette di accordare la cavità al laser, il secondo di ottimizzare l'accoppiamento tra membrana e campo in cavità.

Rumore di frequenza misurato rispetto ad una cavità lunga 50mm, Finesse 57000



Target: **1 Hz²/Hz** (10^{-34} m²/Hz) I fase
0.01 Hz²/Hz (10^{-36} m²/Hz) II fase

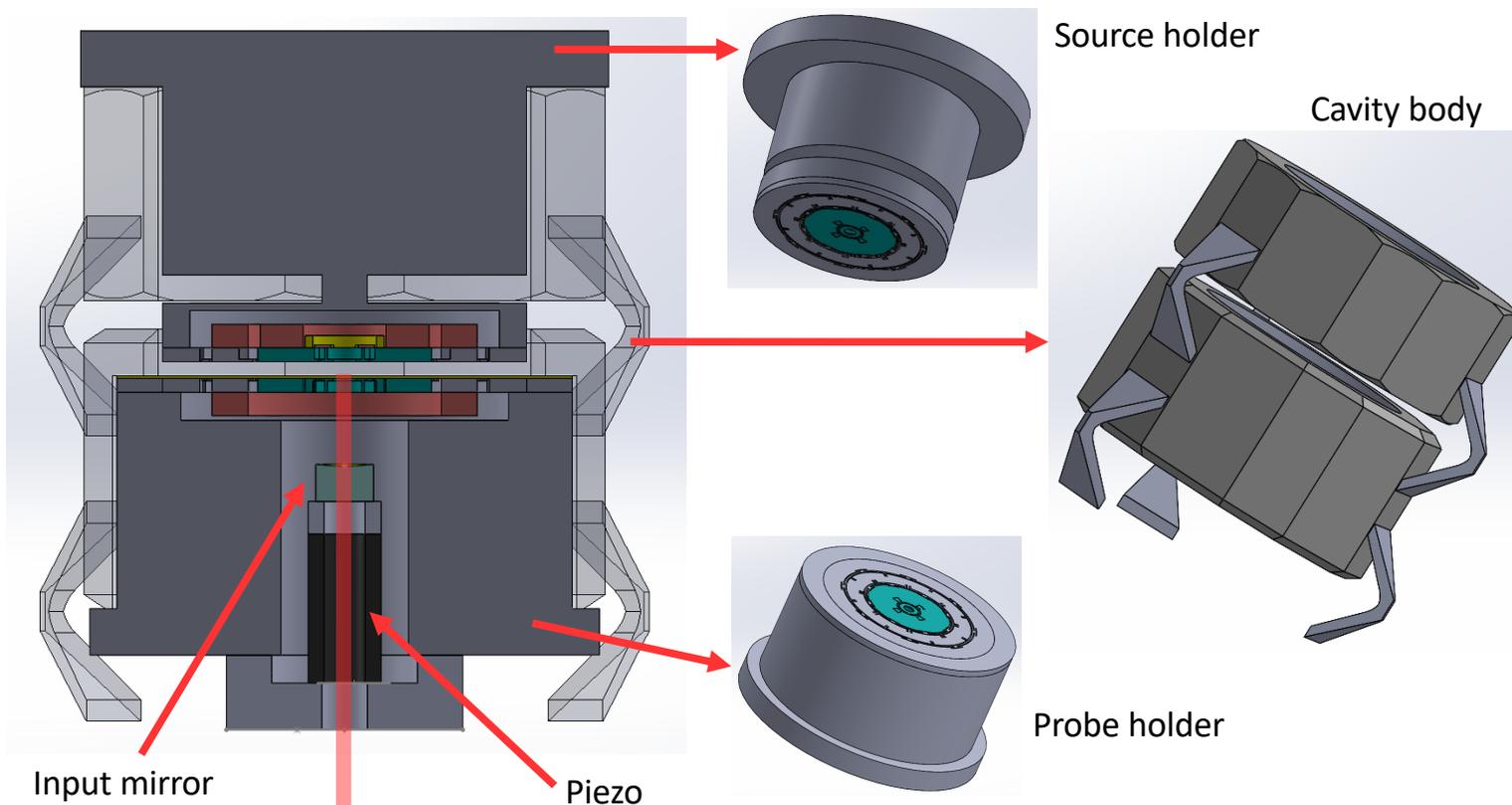
~ 3 mm lunghezza cavità

Si è deciso di procedere con la cavità corta 3 mmn.

Cavity design I (2023 -2024) INFN-TIFPA

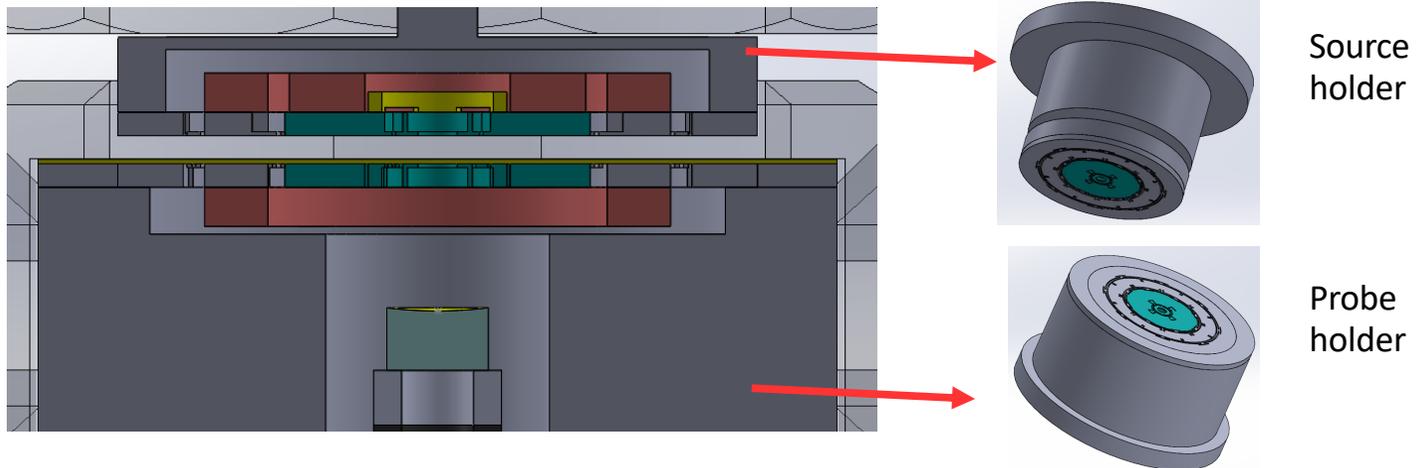
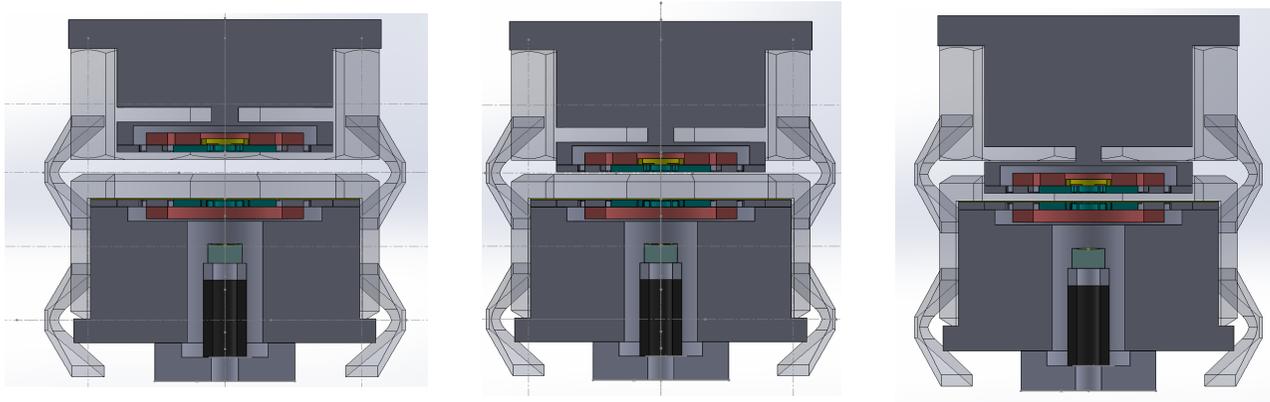
WP6 - CDR

- Disegnata la cavità, da validare a livello di configurazione ottica e termica.
- Misure di conducibilità su contatti metallo/silicio in corso a Camerino.



Cavity design II (2023 -2024) INFN- TIFPA

La lunghezza del Source Holder definisce la distanza tra i due oscillatori (futura movimentazione?)

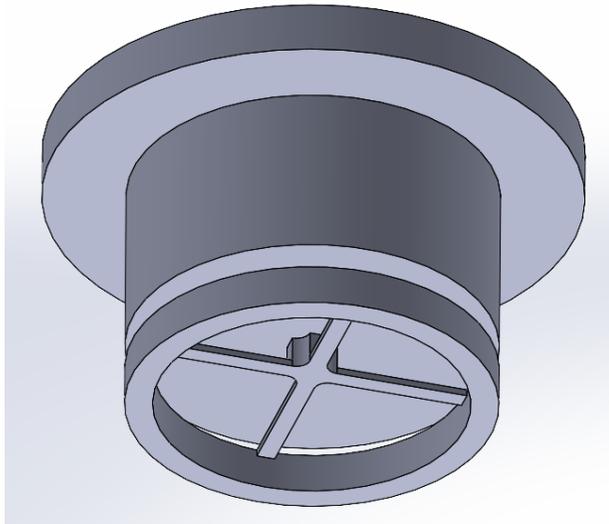


Cavity design III (2023- 2024)

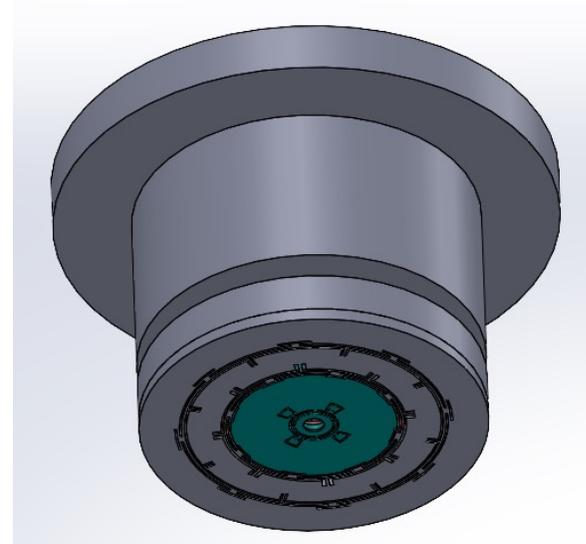
La struttura della **cavità** permette di ottenere la **rieiezione meccanica necessaria per l'esperimento** grazie ad un filtro meccanico aggiunto nel supporto del source.

Questo disegno preliminare permette di migliorare la rieiezione di un fattore 100 (obiettivo CDR). Stiamo lavorando per migliorare di un ulteriore fattore 10 di sicurezza.

NB: il supporto del source deve soddisfare requisiti meno stringenti per la termalizzazione, dato che l'oscillazione di drive è molto maggiore del suo termico. Questo permette maggiore flessibilità di design.



Source Holder

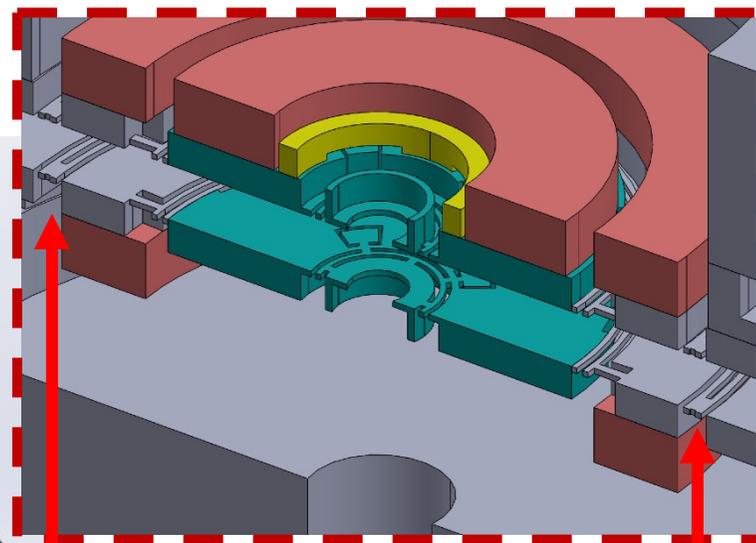
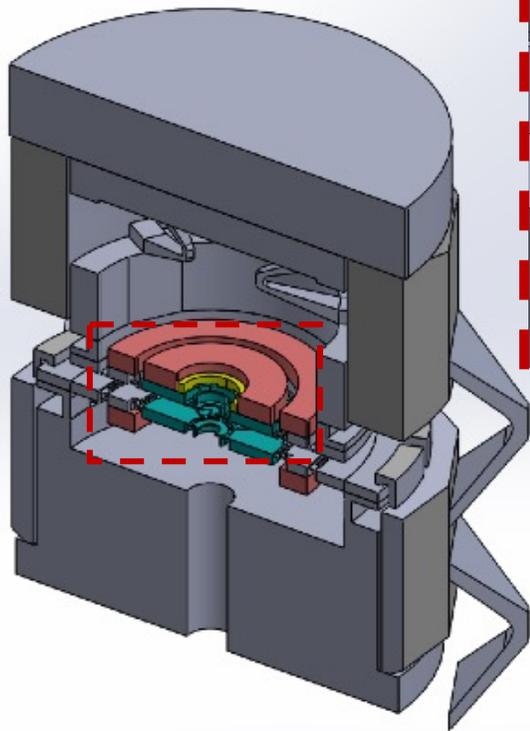
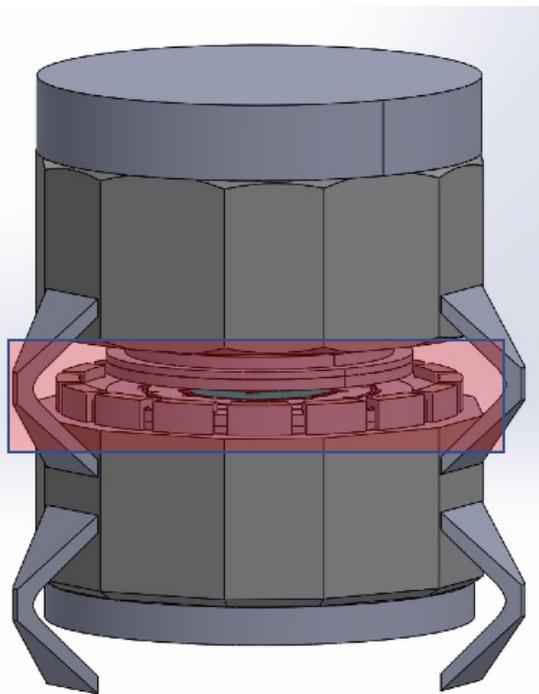


Con Source montato

Cavity design IV (2024 -2025)

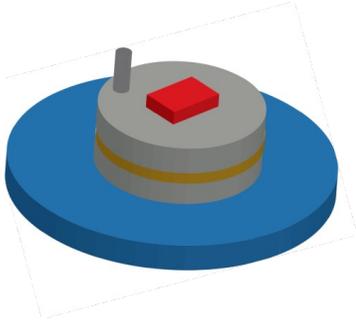
Si è disegnato un nuovo supporto a molle per il clamping non-rigido del Probe e si sono ridefinite le dimensioni giunti flessurali nel silicio al fine di aumentarne la flessibilità e ridurre gli effetti di thermal stress alle temperature criogeniche fino a 20 mK.

Non è una soluzione definitiva in quanto con I dati attuali sui materiali utilizzati nelle simulazioni FEM si prevede ancora una rottura fragile dei giunti esterni. Stiamo aspettando i dati di conducibilità termica da INFN-PG con le dorature di INVAR e Cu.



Rottura del silicio in corrispondenza dei giunti flessurali più esterni

INFN-PG



Il gradiente è determinato dalla resistenza di contatto termico di Kapitza

Attesa ulteriore riduzione con doratura INVAR e Cu.

Misure necessarie per TIFPA

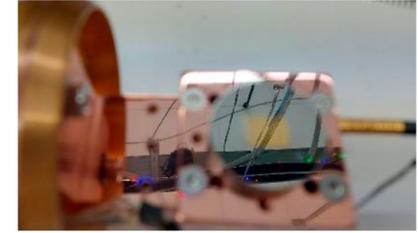
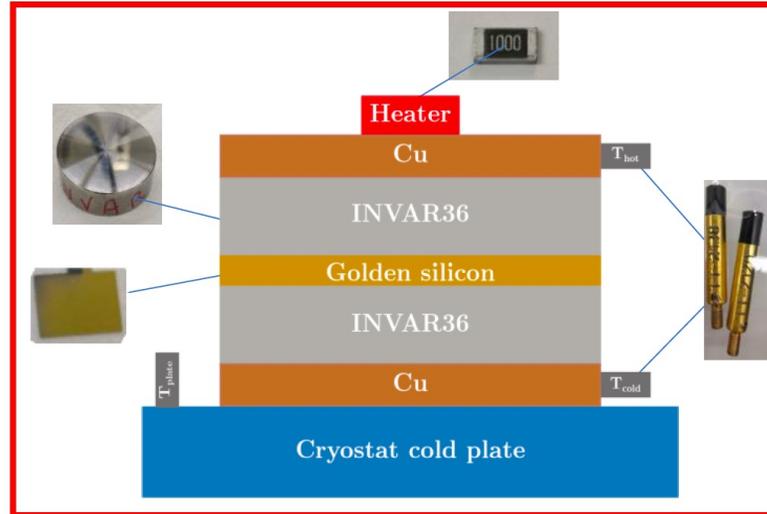
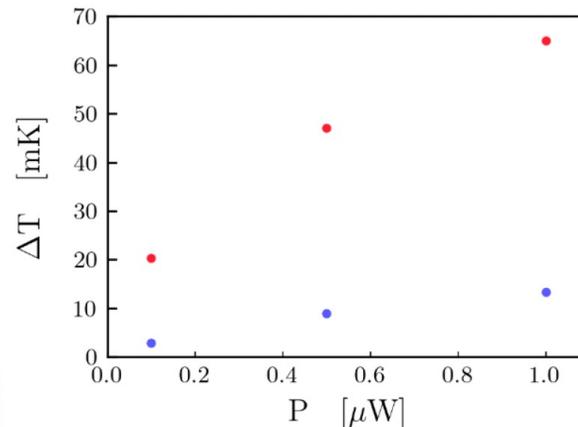
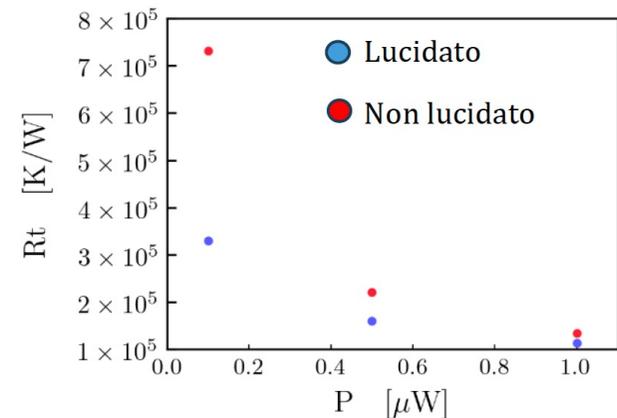


Figura 4. Configurazione del dispositivo per la misura del gradiente termico per la stima della temperatura efficace del campione di silicio. Immagine del dispositivo assemblato (basso a destra).

Gradiente Rame - Rame

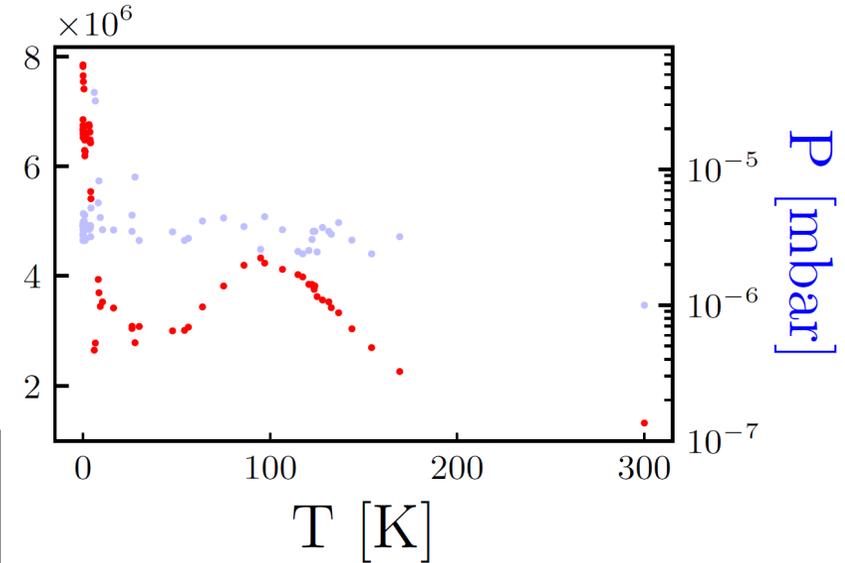
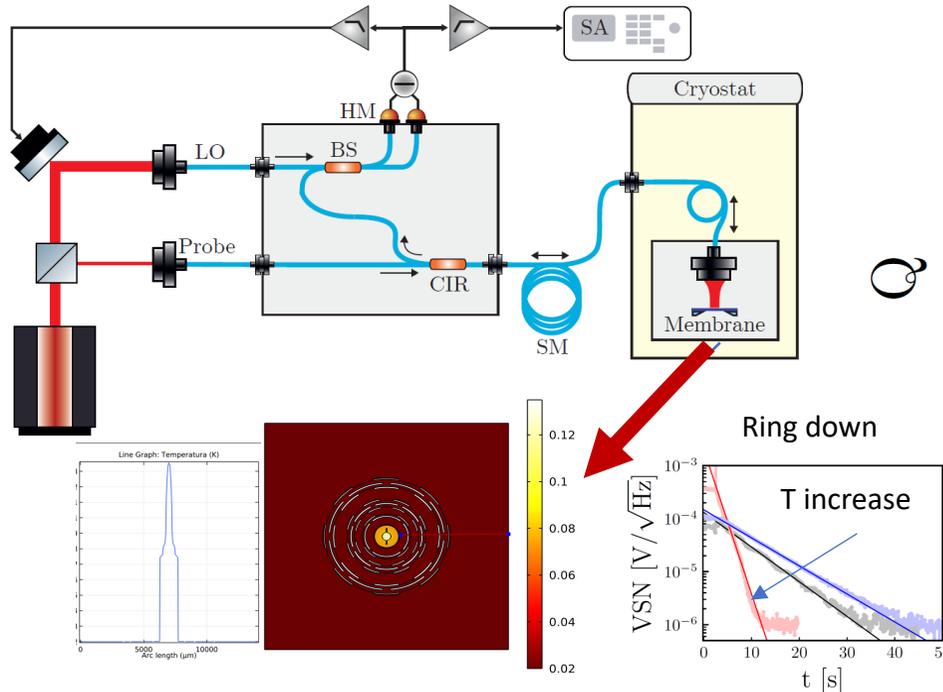


Resistenza termica



Membrana metallizzata in criogenia

Caratterizzazione del fattore di qualità di una membrana circolare di Si_3N_4 metallizzata con TiN.

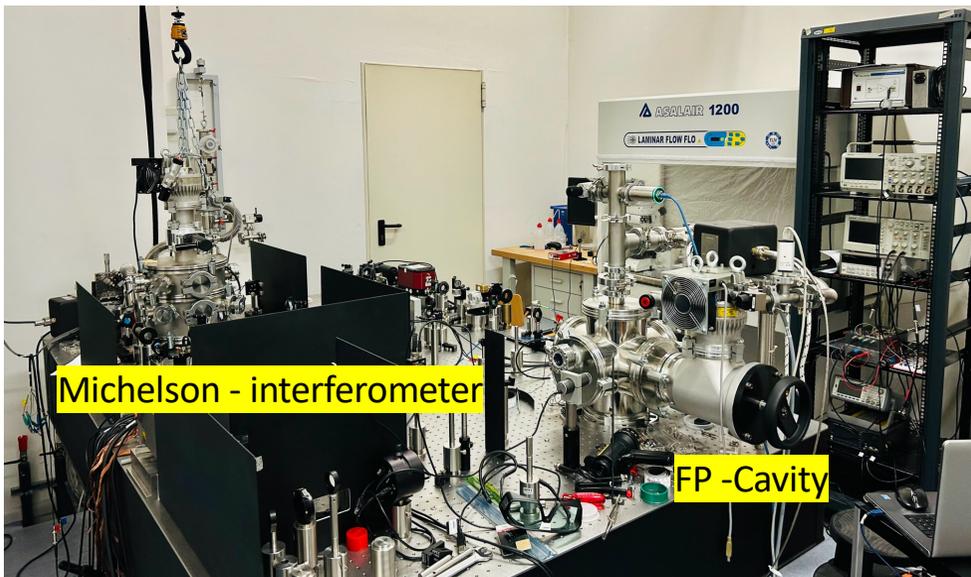


- _ Il fattore di qualità aumenta al diminuire della temperatura.
 - _ Quando la temperatura è al di sotto di 1 K Q è circa 8 milioni.
 - _ Stiamo implementando un sistema di misura stroboscopico perché a $T < 1$ K, $6 \mu\text{W}$ di laser incidenti sulla membrana sono sufficienti a scaldare la membrana, facendo di minuire Q .
- Da misure preliminari abbiamo visto che con misure stroboscopiche per $T < 500$ mK, Q raggiunge il valore di circa 20 milioni.

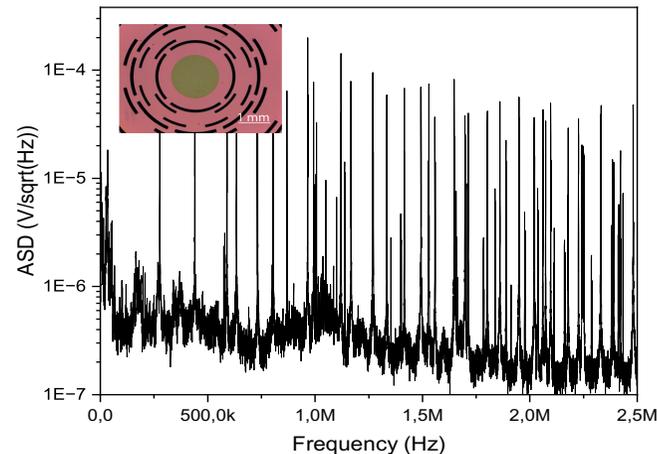
Courtesy from Paolo Piergentili INFN-PG Group

Sinergia con FBK – (2024 -2025)

CNR-IMEM Lab

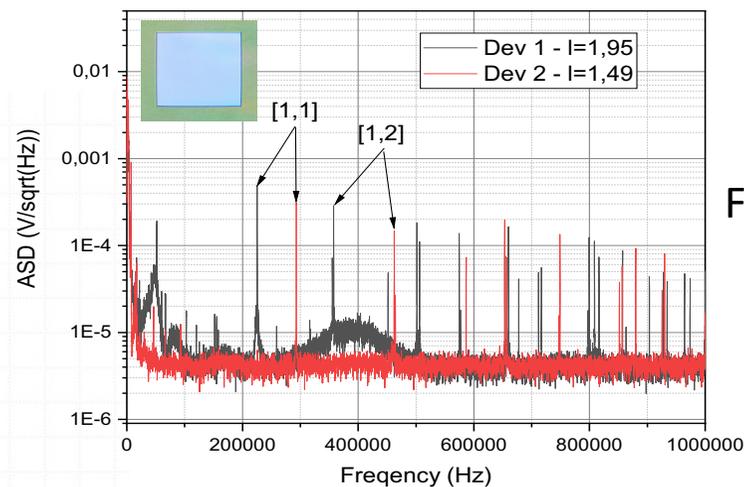


(Top) Cavity measurement with PHD scheme and MIM
 (Bottom) Interferometric measurement on FBK SiN membranes.



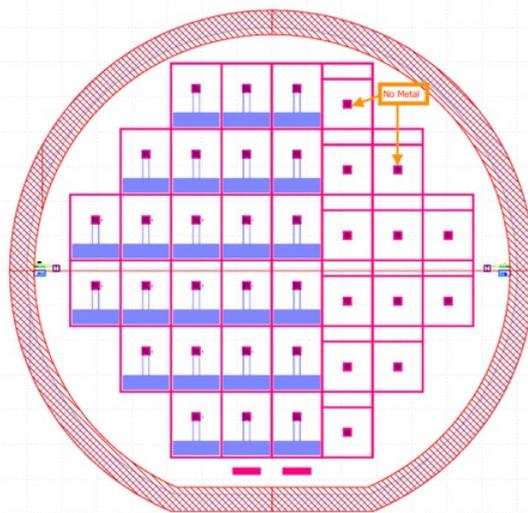
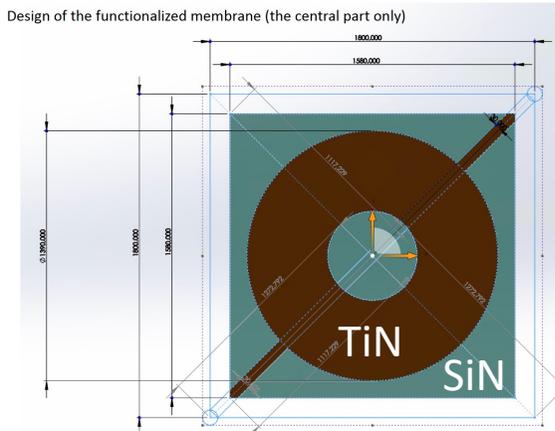
TUD

Nuovo batch di membrane funzionalizzate inserito nell'accordo MiNATAP FBK per studio dissipazione mebrane senza ossido sacrificiale.



FBK

FBK Picciotto, Nawaz, Crivellari, Alberto



20000 μm

Accordo di Ricerca Collaborativa con Sintef Digital (Oslo, Norway) per la microfabbricazione e affidamento servizio microfabbricazione (2024)

WP1 - CDR



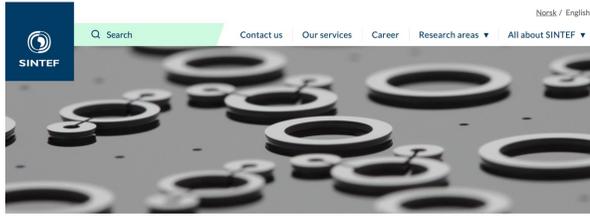
Firmata NDA tra Sintef – Digital e INFN propota da Tecnologico di INFN. Si definisce il flusso di informazioni scambiate tra le parti e la policy di protezione dell'IP che si svilupperà;



Definito l'accordo quadro di ricerca collaborativa TTB_23TIF_089 è di durata annuale e collaborazione con l'ufficio di Trasferimento Tecnologico di INFN che rinnovabile tacitamente per i successivi anni, salvo disdetta anticipata delle parti; L'accordo ha consentito di mantenere il contributo INFN ragionevolmente in linea con l'impegno di spesa programmato in fase CDR.



La fornitura di wafer 6 spessi 1.5 mm è disponibile. Si sta procedendo con RDA e contratto di affidamento diretto servizio di microfabbricazione secondo d.lvo. 36/2023 (nuovo codice appalti)



Department of Smart Sensors and Microsystems

**Collaboration Agreement
(n. TTB_23TIF_089)**

Between

Istituto Nazionale di Fisica Nucleare (hereinafter "INFN"), an Italian Governmental Organization with its seat in via Enrico Fermi 54, 0044 Frascati (RM), Italy, represented by the Director of Trento Institute for Fundamental Physics and Applications (TIFPA), Francesco Pederiva

And

SINTEF AS, by its institute SINTEF Digital, department Smart Sensors and Microsystems, (hereinafter "SINTEF"), having a place of business at Gaustadalleen23 C, 0373 Oslo, Norway, represented by the Research Manager of Silicon Sensors Technology Group, Klaus Magnus Johansen.

hereinafter referred to as the "Party" and, if jointly, the "Parties."

WHEREAS

- I. INFN is an Italian Public Research Organization which promotes, coordinates, and carries out scientific research in the field of nuclear, subnuclear, astroparticle physics and of the fundamental interactions, as well as research and technology development relevant to the activities in these areas by providing synergies with other research institutions and the business world.
- II. INFN, in accordance with article 2 of its Statute, promotes and participate to collaboration, signs conventions and agreements with entities, societies and enterprises, both Italian and International, and international organizations, for study, research and services purposes.

Signed on December 2023

Difficoltà riscontrate sull'uso e abilitazioni nel portale NovaPA. Comunque acquisti GRAFIQO sono state eseguite su portale MePA in modalità TD secondo regole nuovo codice.

Interesse reciproco per l'acquisizione di nuove competenze nel campo risonatori N/MEMS per la gravitazione.



Microsystems and Nanotechnology

Firmato Accordo di ricerca collaborativa del Trasferimento Tecnologico – INFN. Con RDA si affida il Servizio di microfabbricazione. Ridefinito il capitolato tecnico da sottomettere sul portale NovaPA.

E' stato assegnato nel 2024 da CSN2 l'intero importo del servizio 120.k + IVA.

Richiesta Di Acquisto **numero 140816** del 19-04-2024

Stato Attuale	Inserimento Richiesta
Richiedente	Serra Enrico
Ultima modifica	24-05-2024 09:47:39
Riferimento precedente RDA	
Tipologia di Acquisto *	Acquisto Standard
Oggetto *	Servizio di nano/microfabbricazione finalizzato alla realizzazione di prototipi di oscillatori in silicio allo stato dell'arte per studi di gravità quantistica
Materiale/Attrezzatura Pericolosa	<input type="checkbox"/>
E' prevista manodopera all'interno delle nostre sedi (art.26 DLgs 81/08)	<input type="checkbox"/> Guida sulla dichiarazione con o senza interferenze
Struttura della RUP *	Centro Nazionale Scientifico Tecnologico *Trento Institute for Fundamental Physi
RUP *	Manea Christian
*Acquisto di ...	Servizi
Sede di consegna *	Centro Nazionale Scientifico Tecnologico *Trento Institute for Fundamental Physi

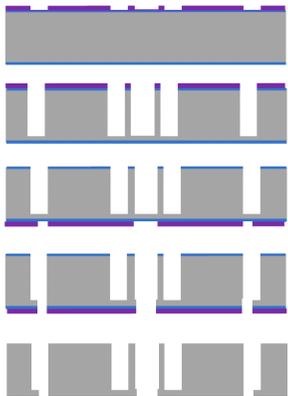
Validazione dei tasks intermedi (2023-2024)

WP1 - CDR

Per lo sviluppo ex-novo di un sistema di risonatori in silicio monocristallino è necessaria la validazione dei task intermedi di processo che hanno come risultato un singolo device o parti di esso. La validazione permetterà aggiustamenti del design iniziale o miglioramenti della meccanica del sistema risonante.

Esempio di possibile realizzazione del SOURCE (process flow-chart)

First fabrication process – Task 1



1. Hard mask and litho mass side
2. RIE and DRIE for defining the 250 μ m thick membranes
Since the opening are quite uniform the result here should be good
3. Litho on spring side
4. RIE and DRIE etching of the springs.
5. Oxide strip and cleaning

Esempio di possibile realizzazione della membrana del PROBE (process flow-chart)

First fabrication process – Task 2



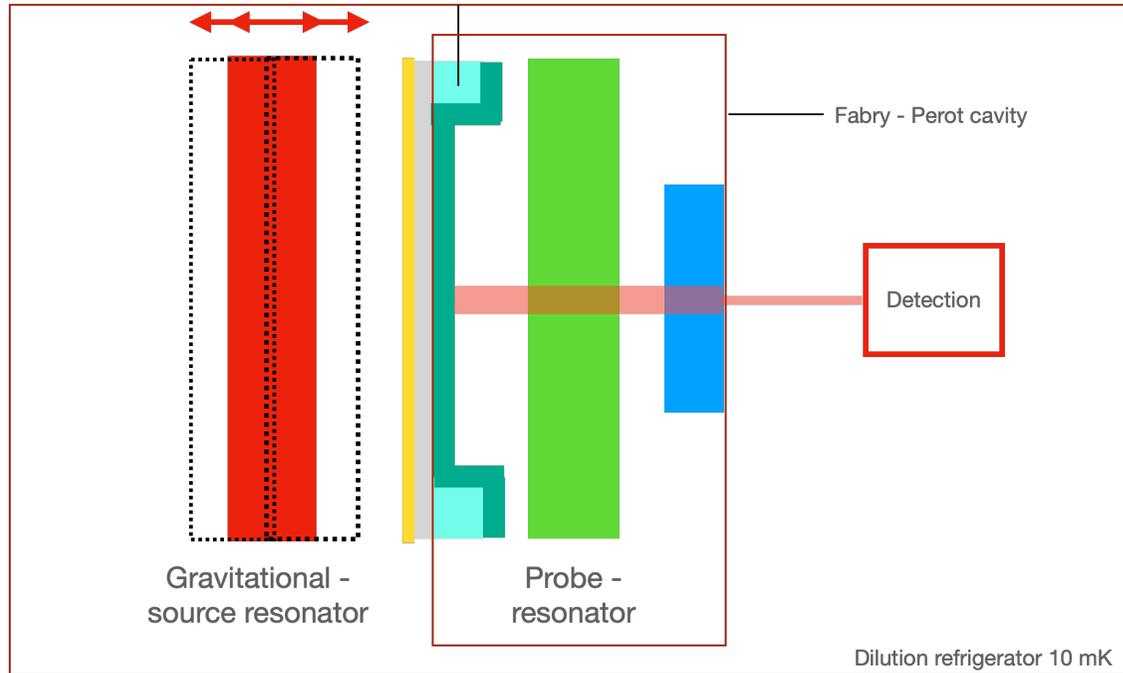
1. 280 μ m thick wafer with Silicon Oxide
2. LPCVD nitride deposition
3. 1 side removal and stress measurements
4. Etch of the membrane
5. VHF release of the membrane

HR coating/shield development (2024-2025)

WP3 - CDR

Shield & UHR mirror component

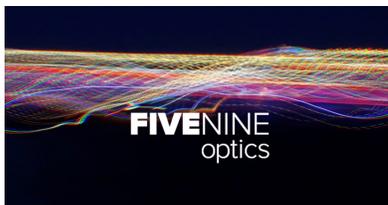
TO BE DEVELOPED



Task: Microfabrication of a bi-functional component with one side coated with gold while the other side with a UHR Double Bragg Reflector – target reflectivity: 99.999% (total loss <30 ppm)

Deposition of the UHR-DB coating will be done FiveNine Optics (USA)

TU Delft - Else Kooi Lab will produce the component at the Microfabrication facility. Collaboration with the THz Sensing group.

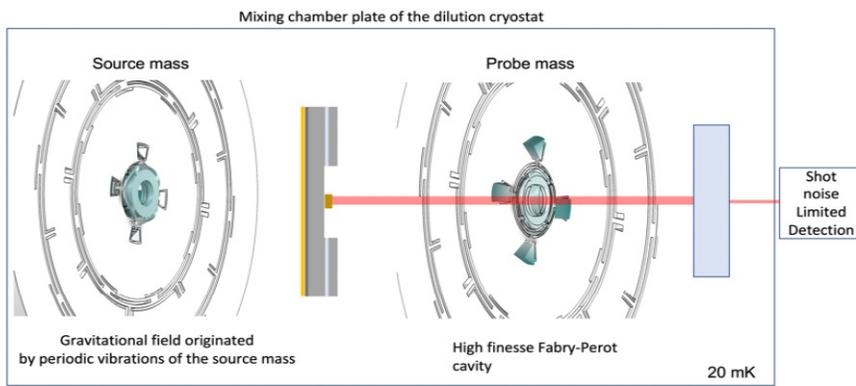


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Suite A
Boulder, CO 80301
USA

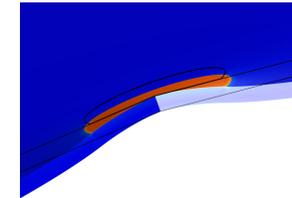


involved in the characterisation of the low loss coating

State of the art for IR low loss High-reflecting coatings



Deformation



Intrinsic stress in 5.9 um HR coating

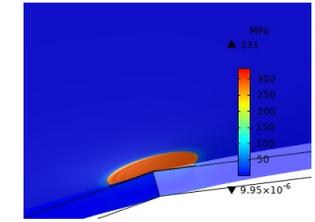
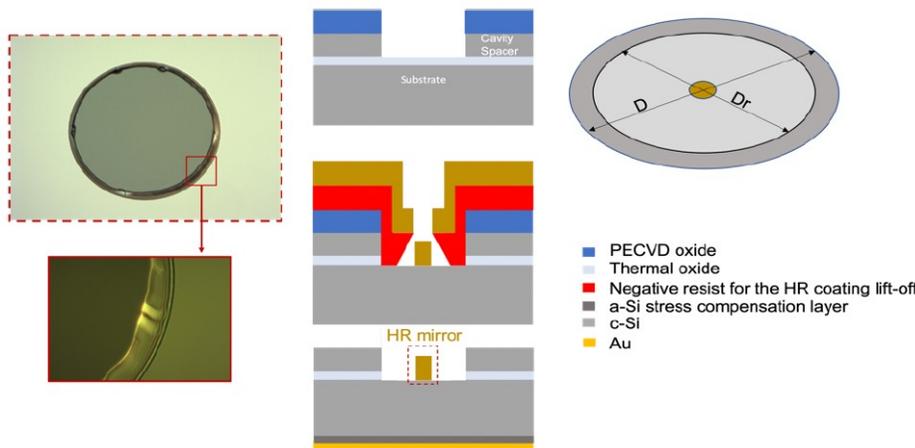
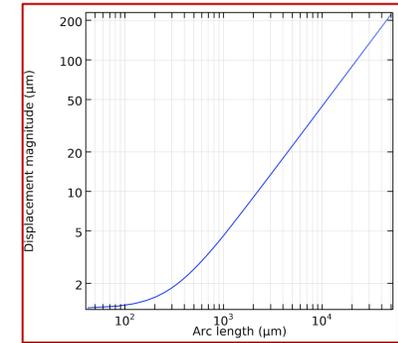


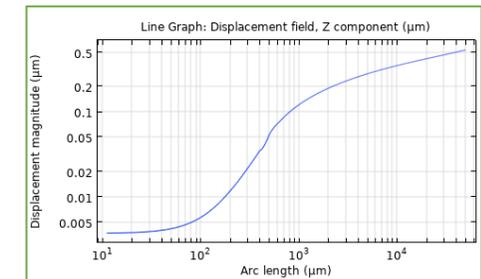
Figure 1: Schematic depiction of a segment of the experimental arrangement designed to measure the gravitational gradient between two masses of milligram scale - the Source (stimulated electrically) and the Test (utilized for read-out) - within a dilution refrigerator. The separation between the masses needs to be approximately $< 500 \mu\text{m}$ to generate an anticipated force of 1.26 pN/m .



Full-coated device
20 um of deflection !!
Unacceptable !!



Partially-coated device $< 500 \text{ nm}$



CTE stress must be evaluated at 20 mK.

Figure 2 (left): Optical depiction of the HR-mirror, meticulously cleaned with RCA-1, boasting an impressive reflectivity of 99.999%. This achievement was accomplished through the Ion-Beam-Sputtering (IBS) deposition of $\lambda/4$ layers consisting of $\text{Ta}_2\text{O}_5/\text{SiO}_2$ (38 layers). (right) a schematic outlining the main stages of the microfabrication process. It commences with a silicon-on-insulator wafer featuring a cavity-spacer representing a device layer, while the handle wafer sets the minimum distance between the oscillators.

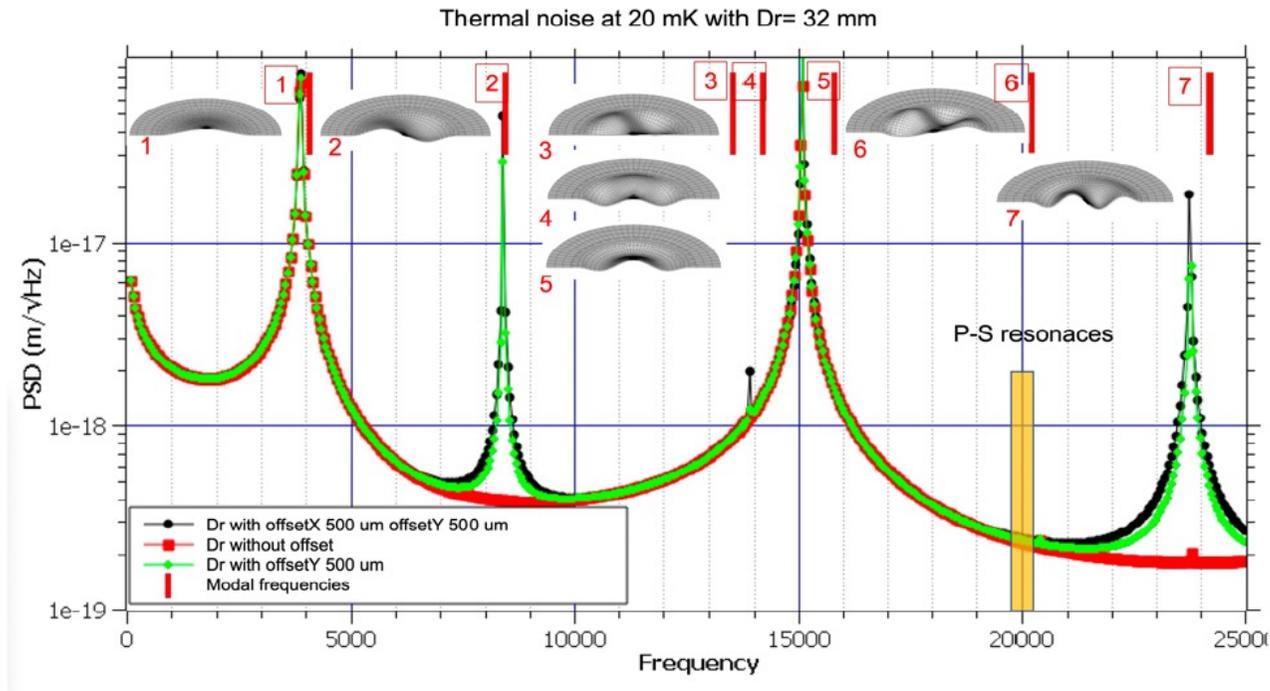
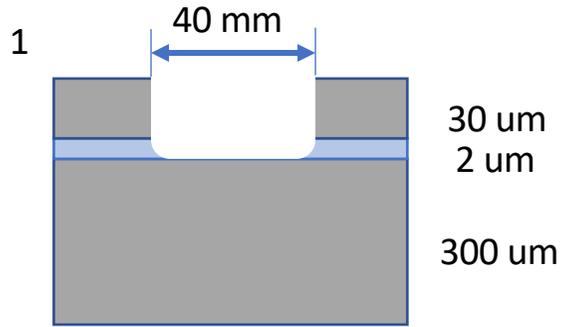
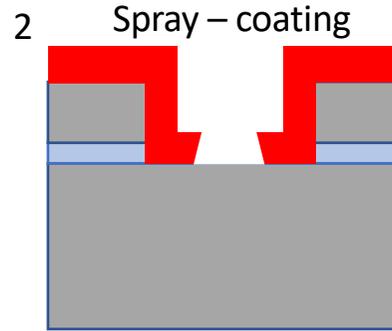


Figure 3 presents the thermal noise background (Power Spectral Density) of the silicon mirror, primarily due to structural dissipation at the read-out port of the HR mirror. The substrate thickness is $270\ \mu\text{m}$, with modes structural damping dominated by the support at 10^3 . Using Finite Element full harmonic analysis within the $[0\text{-}25\text{kHz}]$ bandwidth, the collective mode contribution is thoroughly evaluated. Modal shapes of the first seven modes are depicted. The impact of read-out misalignment, both in X and Y directions ($500\ \mu\text{m}$), and in one direction Y, is assessed. Notably, the mirror meets the stringent experimental requirements for the quantum gravity experiment ($< 10^{-18}\ \text{m}/\sqrt{\text{Hz}}$) within the bandwidth of the Probe-Source oscillators.

New process for integrating the HR coating/schield

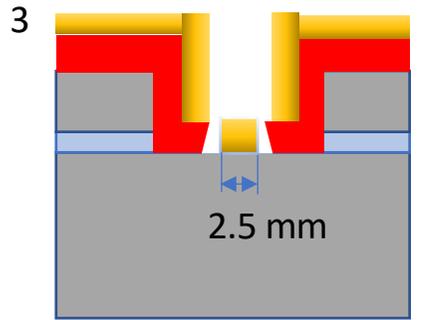


Silicon-on-Insulator wafer with a cavity (made by DRIE)

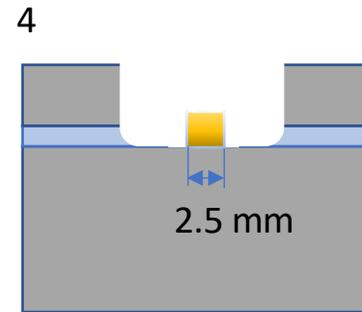


■ nlof2070 or ma-N 490 – 7.8 um thickness

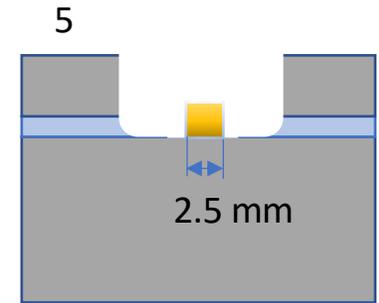
	Thickness [um]
Au (evaporated)	0.1-0.5
Cr/Ta (Adhesion layer)	0.005
Si	300
UHR – coating Ta2O5/SiO2	5.9
Spacer device layer SOI	10 um



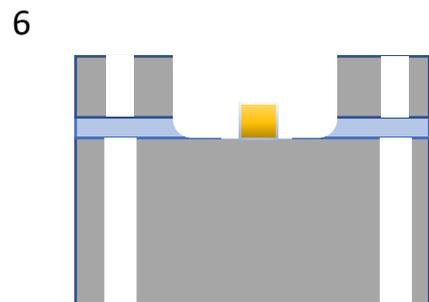
■ High-reflecting coating IBS sputtering



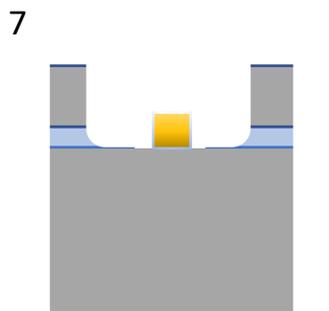
Lift-off - Resist strip NMP ((1-methyl-2 pyrrolidone) 80 °)



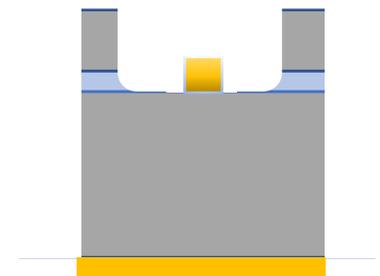
Stabilization annealing 430°C – 450°C



Double side Deep-RIE



Buried oxide removal with BHF/dicing/cleaning



Au coating by evaporation/ HR coating protection removal

GRAFIQO Workpackages

Attività TIFPA 2025

WP1: Progettazione e realizzazione di dispositivi P-S
WP3: Studio e riduzione dell'accoppiamento elettrostatico.
WP5 Analisi ed eventuale riduzione del rumore acustico a 20 kHz.
WP6 Progettazione e realizzazione del sistema opto-meccanico

- Processo di microfabbricazione per P-S (Acquisto servizio microfabbricazione Sintef)
- Microfabbricazione specchio HR/schermo
- Design definitivo della cavità con sistema di reiezione meccanica cross-talk tra PS migliorata di un fattore 1000.
- Design del supporto per oscillatori che prevenivano rotture dovute alle contrazioni differenziali in criogenia.

Impegni di spesa/missioni GRAFIQO	al 30/06/2024	al 31/12/2024
Costo incompressibile e non divisibile in 3 anni (come previsto nel CDR) per fabbricazione microoscillatori SINTEF di cui 50 k€ da restituzione 2023 e 50 k€ da anticipo 2025	-	146200 € (entro settembre)
Acquisto materiale consumabile per setup banco ottico	3886,92 €	-
Storno a FBK_CSN2 per la realizzazione di dispositivi MEMS (provini di test contenenti membrane in nitruro di silicio su substrato privo di ossidi di silicio - 1 maschera equivalente) nell'ambito della convenzione INFN-FBK	2500,00 €	-
Oneri doganali per acquisto wafers 6-inch Silicon	793,00 €	-
Missioni coordinamento Italia / missione estero TUD / Sintef	418,47 €	6500,00 €

- *Strain-Engineered SiN Nanomembranes for Room-Temperature Quantum Optomechanics* - To be submitted to MDPI Photonics - Special issue: Advancements in Optomechanics: from Fundamental Physics to Quantum Sensors; 2024

- *Design and microfabrication of ultra-high reflective mirror for quantum optics*, 50th International Micro and Nano Engineering Conference, September, 16th - 19th 2024 Montpellier France

- *Low Noise Opto-Electro-Mechanical Modulator for RF-to-Optical Transduction in Quantum Communications*, Frontiers of Quantum and Mesoscopic Thermodynamics Conference, 21-27 July 2024, Prague, Czech Republic

FTE & richieste finanziarie TIFPA 2025

Dettaglio FTE - TIFPA	2024
Dr. Michele Bonaldi (Associato Dip. FBK-CNR)	1.0
Dr. Antonio Borrielli (Associato Dip. CNR-IMEM)	1.0
Dr. Serra Enrico (Dip. Tecnologo TIFPA)	0.5
TOT	2.5

- Nota: Sono previsti 0.2 FTE per PRIN2022-Prot. 2022KP2N2L - *Quantum transduction and sensing with opto-electro-mechanical systems* – sinergico a GRAFIQO

Rimandiamo acquisito Au Coater

Richieste finanziarie TIFPA	2025
Processo microfabbricazione (quota annuale per rimborso spese CR - Accordo di Ricerca collaborativa) –consumabile - già erogato nel 2024 per acquisto servizio fabbricazione Sintef 120k + IVA.	40k
Missioni italia (coordinamento 3 persone) e estere (TUD & Sintef Digital – min. 2 viaggi)	10k
Lavorazioni meccaniche per supporti (caratterizzazione Q meccanico Probe-Source)	3k
Acquisto di silicon substrate (SOI o monolithic)	4k
TOT	17k

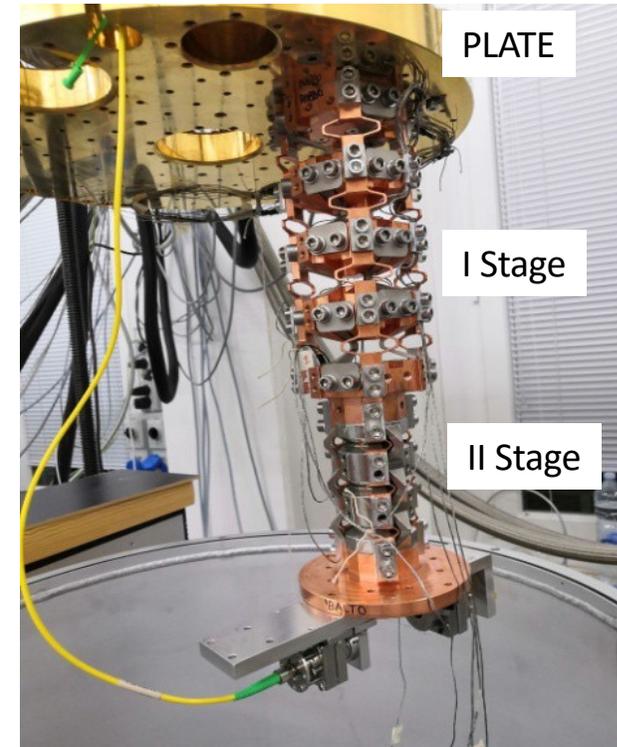
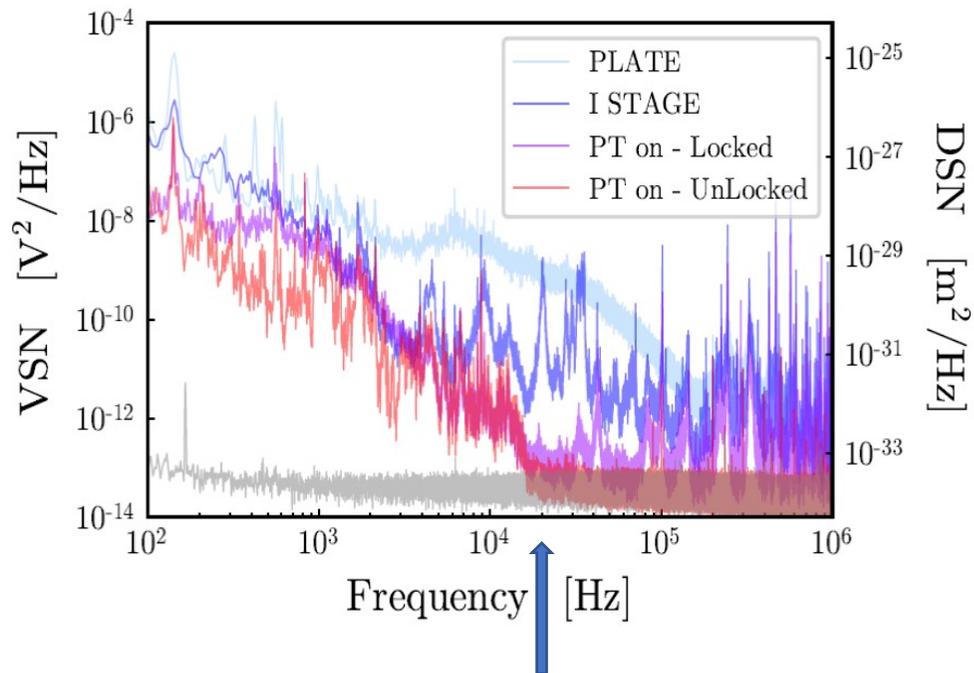
Publications 2023

Amplitude and phase noise in two-membrane cavity optomechanics	Marzioni, Francesco  et al.	FRONTIERS IN PHYSICS	DOI	Show
Low Noise Opto-Electro-Mechanical Modulator for RF-to-Optical Transduction in Quantum Communications	Bonaldi, Michele et al.	ENTROPY	DOI	Show
Microwave Quantum Illumination with Correlation-To-Displacement Conversion	Angeletti, Jacopo et al.	PHYSICAL REVIEW APPLIED	DOI	Show
Optical self-cooling of a membrane oscillator in a cavity optomechanical experiment at room temperature	Veziro, P.  et al.	PHYSICAL REVIEW A	DOI	Show
Quantum state purity versus average phonon number for characterization of mechanical oscillators in cavity optomechanics	Borkje, K.  ; Marin, F. 	PHYSICAL REVIEW A	DOI	Show
Spectral Analysis of Quantum Field Fluctuations in a Strongly Coupled Optomechanical System	Ranfagni, A. et al.	PHYSICAL REVIEW LETTERS	DOI	Show

Background noise in the cryostat (2023)

WP5 - CDR

Reduction of background noise floor I:
reducing **mechanical vibration and acoustic noise** with suspension system
(good preliminary results)



PT – Pulse Tube
Optical Cavity Locked/ Unlocked