Istituto Nazionale
di Fisica Nucleare

TIFPA

Trento
Institute for
Fundamental
Physics and
Applications

Development of femtoAmpere photo-current measurement facility in preparation of LISA Charge Management System end-to-end discharge test

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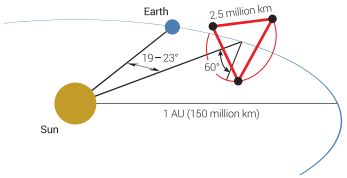
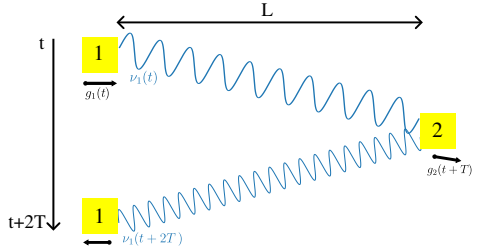
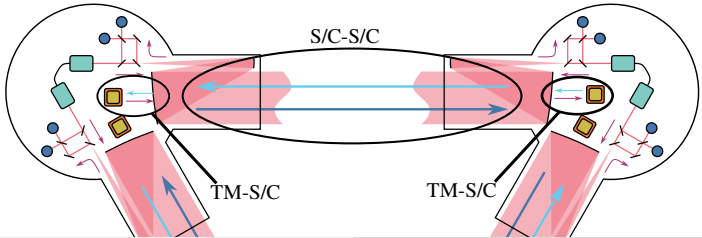
Laser Interferometry Space Antenna (LISA)

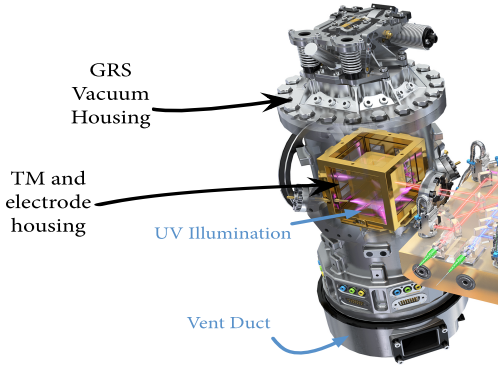


$$\frac{1}{\nu_1}\frac{d}{dt}\delta\nu = \overbrace{\frac{1}{2}\left[\dot{h}_+(t+2T) - \dot{h}_+(t)\right]}^{\text{gravitational wave}} + \overbrace{\frac{1}{c}\left[g_1(t) + g_1(t+2T) - 2g_2(t+T)\right]}^{\text{stray accelerations}} + \underbrace{\frac{1}{\nu_1}\left[\dot{\nu}_1(t) - \dot{\nu}_1(t+2T)\right]}_{\text{laser frequency fluctuation}} + \underbrace{\frac{1}{\nu_1}\left[\dot{\nu}_{n1}(t+2T) + \dot{\nu}_{n2}(t+T)\right]}_{\text{interferometer readout noise}}$$



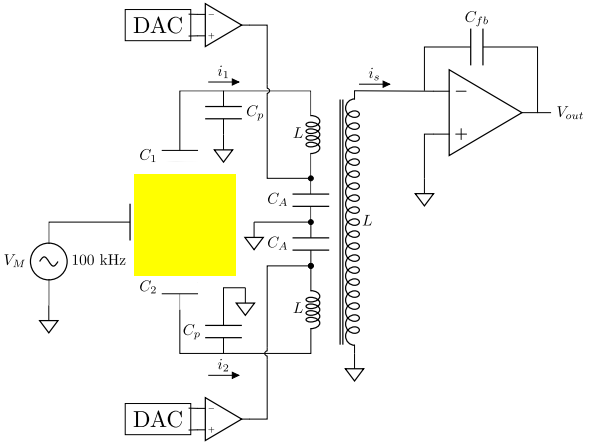


Gravitational Reference Sensor(GRS)

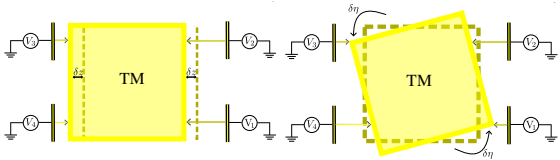


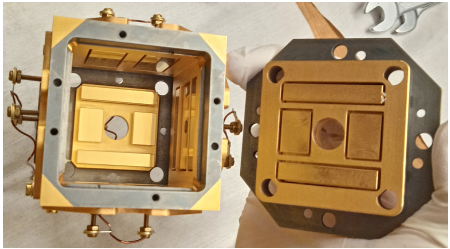
- Test Mass: free-falling geodesic reference
- Electrode Housing: capacitive position sensing($nm/\sqrt{Hz}$) and force actuation(nm/s^2)
- Charge Management system: discharges the test mass shining UV light
- Caging systems: keep the test mass in place during lunch and release it with μm/s residual velocity
- Vacuum chamber: provide controlled environment

Capacitive Sensing and Actuation



Schemes for linear and angular actuation



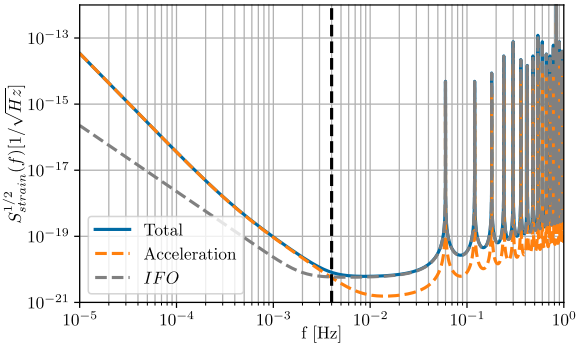


LISA Noise Requirements

Strain equivalent noise PSD

$$S_{strain}(\omega) = \frac{2}{c^2\omega^2 \sin^2 \omega T}\left[4S_g + \omega^4 S_{IFO}\right] + 4S_{\delta\nu/\nu}$$

Observation band 0.2 mHz-1 Hz



numbers from LISA Red Book

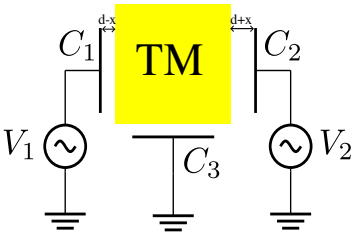
Test Mass acceleration noise

$$S_g^{1/2} \leq 3\,\mathrm{fm/s^2/\sqrt{Hz}} \times \left[1 + \left(\frac{0.4\,\mathrm{mHz}}{f}\right)^2\right]^{1/2} \times \left[1 + \left(\frac{f}{8\,\mathrm{mHz}}\right)^4\right]^{1/2}$$

Interferometer(IFO)

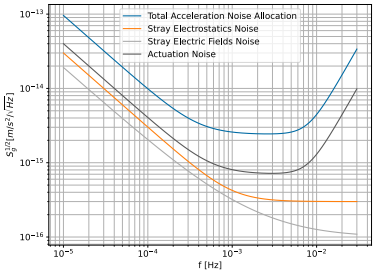
$$S_{IFO}^{1/2} \leq 10\,\mathrm{fm/\sqrt{Hz}} \times \left[1 + \left(\frac{2\,\mathrm{mHz}}{f}\right)^4\right]^{1/2}$$

Stray Electric Fields and Test Mass Charge



The total Test Mass charge Q_{TM} couples with the residual stray electrostatic fields from the electrods Δ_x into a force(acceleration) noise.

$$F^{Q_{TM}}_{x,noise} = -\frac{Q_{TM}}{C_{TM}}\left|\frac{\partial C_x}{\partial x}\right|\Delta_x \qquad \Delta_x = V_1 + V_2 - V_3 - V_4$$



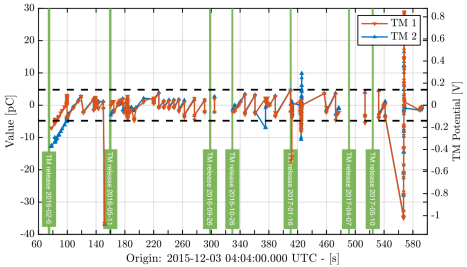
$$S_g^{\Delta_x} = \left(\frac{1}{M_{TM}}\frac{Q_{TM}}{C_{TM}}\left|\frac{\partial C_x}{\partial x}\right|\right)^2 S_{\Delta_x}(f) = \left[2\,\frac{\text{fm}}{\text{s}^2\sqrt{\text{Hz}}} \times \left(\frac{Q_{TM}}{2.4\,\text{pC}}\right)^2 \left(\frac{S^{1/2}_{\Delta_x}}{200\,\mu\text{V}/\sqrt{\text{Hz}}}\right)\right]^2$$

$$\Downarrow$$

$$|Q_{TM}| \leq 2.4\,\text{pC} \Leftrightarrow |V_{TM}| \leq 70\,\text{mV}$$

Charge Management System

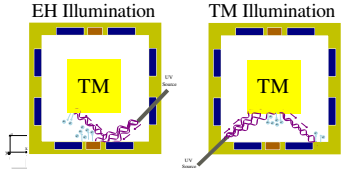
Particles from cosmic ray and solar wind with $E \geq 100\,\text{MeV}$ produce a **net positive charging** of the TMs with rate $\lambda_{net} = 1$ - 100 e/s.



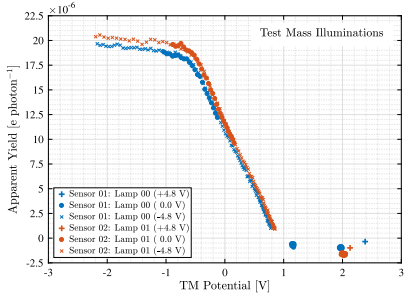
from Charging of free-falling test masses in orbit due to cosmic rays: Results from LISA Pathfinder, Physical Review D 107, 062007(2023)

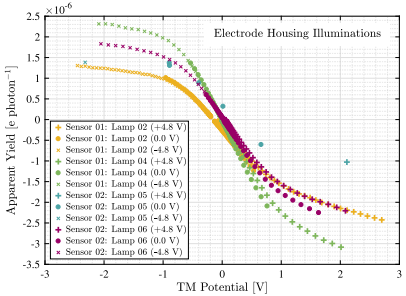
The Charge Menagment System(CMS) counters the charging by discharging the TMs via the photoelectric effect. LISA CMS will shine UV light at $\sim$250 nm($\sim$4.9 eV). Two possible discharge strategies are aviable:

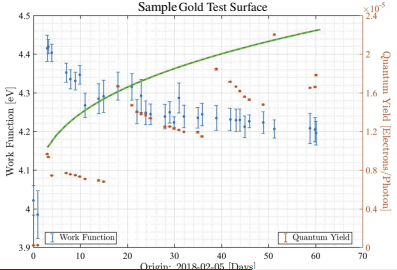
- Fast Discharge: light is shone for 600 s when $Q_{TM} = 2.4\,\text{pC}$ to discharge it to $-2.4\,\text{pC}$, corresponding to a 4 fA photocurrent
- Continuous Discharge: shining light while the TM is around the equilibrium point(possibly at $Q_{TM} = 0\,\text{pC}$), the TMs is kept below the noise requirement, corresponding to a continuous 4 aA photocurrent



Why a new facility?



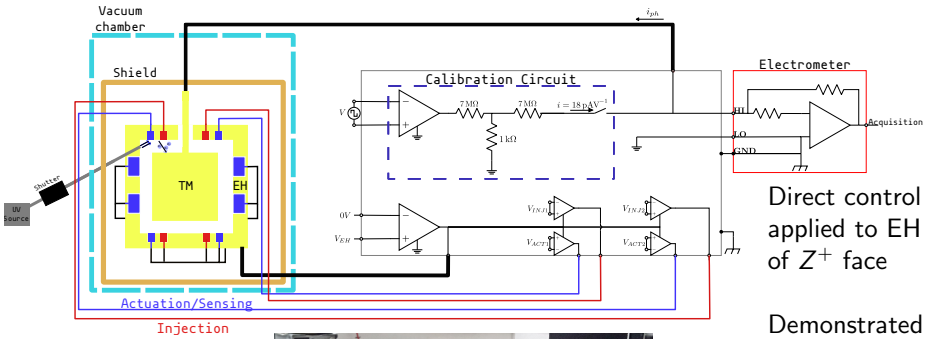


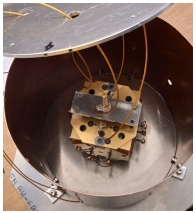


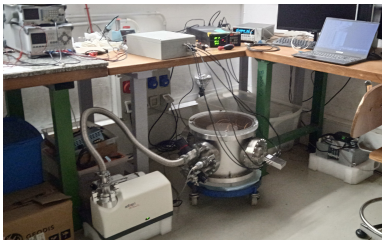
- LPF demonstrated in-flight operability of the system, but with variability of the yield properties for different surfaces
- Yield stability is needed for continuous discharge
- Yield change explanations are qualitative
- Try to replicate the worrying "0-Yield" measurement of LPF testing
- Test with integrated GRS

from Davide Dal Bosoco Ph.D thesis, and Peter Wass et al. work at Imperial College

End-to-end discharge facility





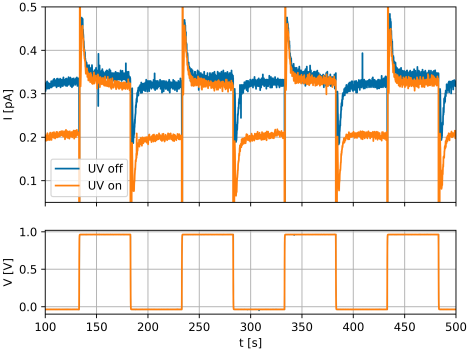


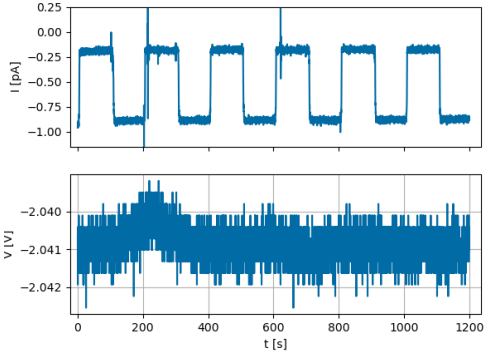
Direct control of potentials applied to EH and electrodes of Z^+ face

Demonstrated sensibility of 0.9 fA with 10 mHz input signal

The measurements have less resolution than the torsion pendulums', but are faster(hours instead of days)

Photocurrent Measurements



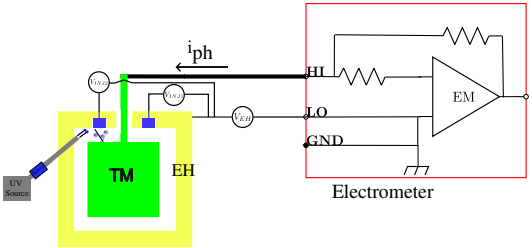


- Modulation of V_{TM}
- Actually $i_m = i(V_{TM}) - i(0V)$
- Need to measure darkcurrent $R_{leakage} \approx 12\,\mathrm{T}\Omega$

- Modulation of light source
- V_{TM} is fixed
- Only one measurement needed

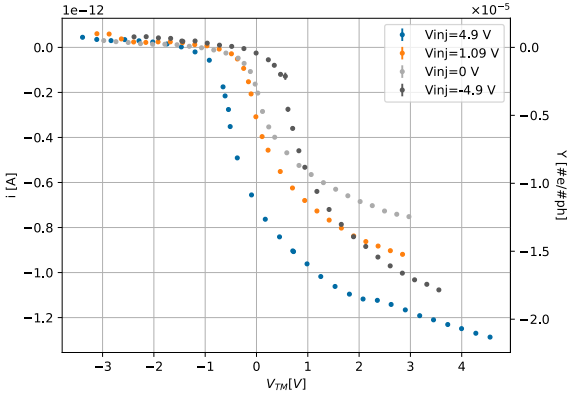
Experimental Discharge Curves

- $V_{TM} = -V_{EH} - \alpha V_{inj}$
- $\alpha = \frac{C_{inj}}{C_{tot}} = 0.12$
- Yield $Y = (I/e)/(P_{UV}/E_{UV})$



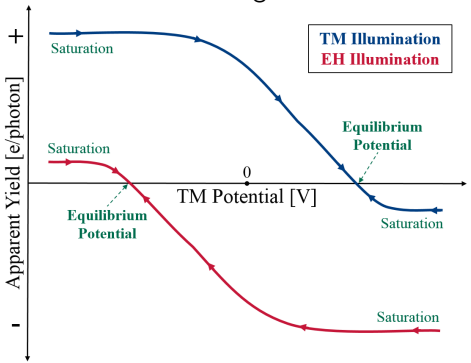
semplified facility scheme

end-to-end facility



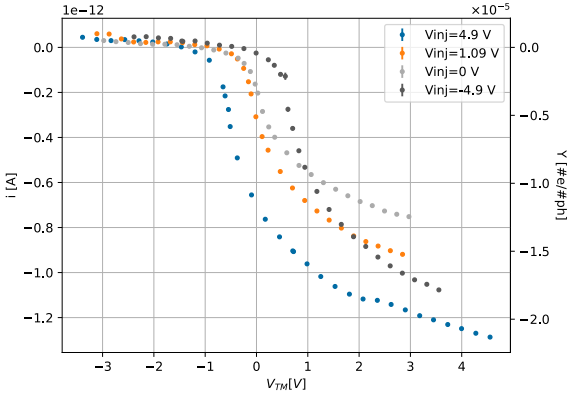
Experimental Discharge Curves

Ideal discharge curves



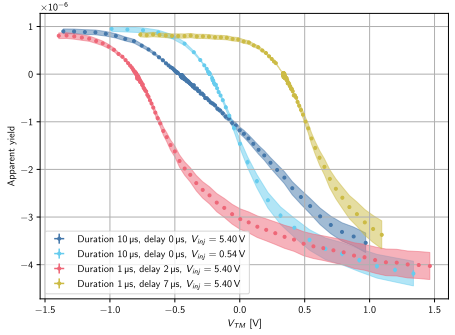
from Davide Dal Bosco Ph.D. thesis

end-to-end facility



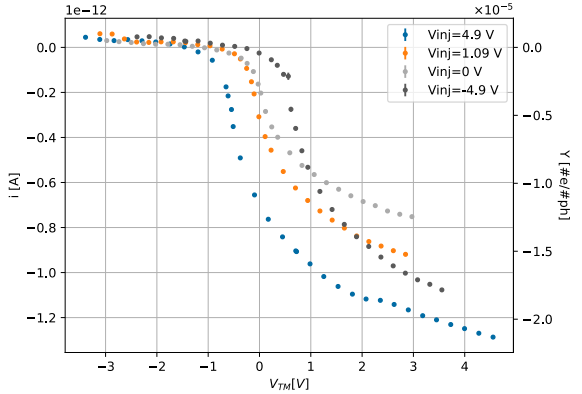
Experimental Discharge Curves

4TM Torsion Pendulum



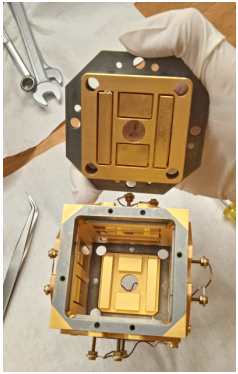
from Davide Dal Bosco Ph.D. thesis

end-to-end facility



Next up

- Verify ability to predict discharge curves for any V_{INJ} applied, knowing the curve for $V_{INJ} = 0\,V$
- Transfer the measurement technique to OHB-I for testing on EM, QM and FM of LISA from next year
- make the facility bake-out capable to repeat the conditions that led to yield disapperance during LPF testing



References

Francesco Venturelli, William Joseph Weber
Development of femtoAmpere photoelectric measurement facility for testing UV test mass discharge for the LISA mission
Master Thesis, University of Trento, 2023

Davide Dal Bosco
Torsion Pendulum Testing of the LISA Charge Managemnet System
PhD thesis, University of Trento, 2023.

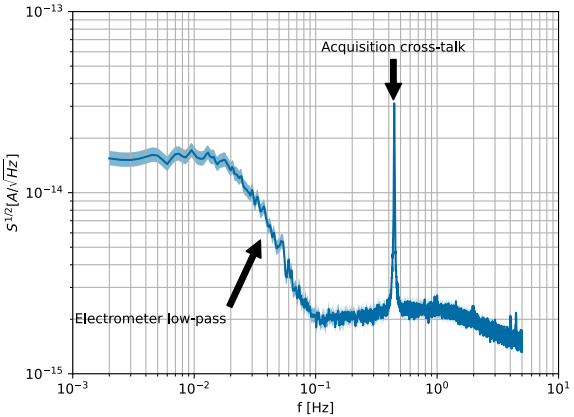
LISA Science Study Team, ESA Study Team
LISA Definition Study Report - LISA Red Book)
Avaiable at https://www.cosmos.esa.int/web/lisa/documents

M. Armano *et al.*
Charging of free-falling test masses in orbit due to cosmic raysL Results from LISA Pathfinder
Phys. Rev. D. vol. 107, 2023.

Peter J. Wass *et al.*
Effective decrease of photoelectric emission threshold from gold plated surfaces
Review of Scientific Instruments, 2019.

Backup Slides

Noise PSD



$$S_i^{1/2}(10\,\mathrm{mHz}) = 16.3\,\mathrm{fA/Hz^{0.5}}$$

$$\sigma_i(10\,\mathrm{mHz}) = \frac{S_i^{1/2}(10\,\mathrm{mHz})}{\sqrt{300\mathrm{s}}} = 0.9\,\mathrm{fA}$$