Torsion-pendulum testing of LISA charge management with a replica LPF gravitational reference sensor

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Davide Dal Bosco

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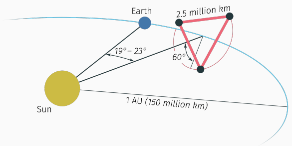
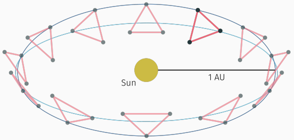
What is LISA and how does it work?

LISA is a **space mission** to detect *gravitational waves*:

- Free-falling test masses are **tidally accelerated** by curvature.
- Relative acceleration is detected as a **frequency modulation** of the received laser beam.
- Spacecrafts have the goal to **protect** the purity of the free fall of test masses.



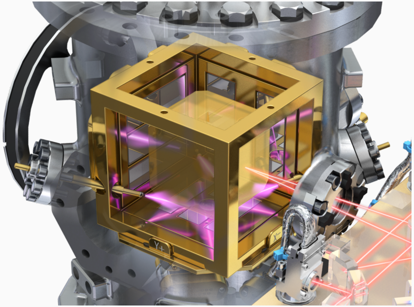


Need for charge management and LPF heritage

Problem

Cosmic rays and SEP charge **positively** the TMs. The net charge rate for CRs is expected to be between $+10\,e/\mathrm{s}$ and $+100\,e/\mathrm{s}$.

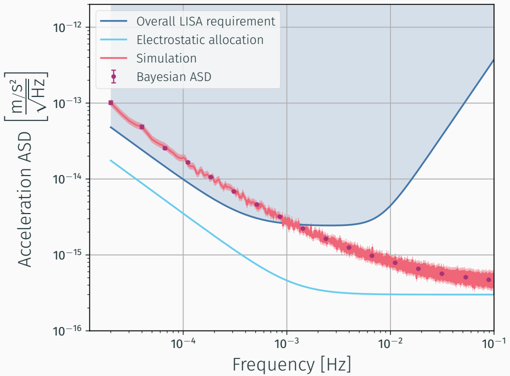
- TM charge is required to be kept in the range $\pm 1.5 \cdot 10^7\, e$ (i.e. $\pm 70\, m\mathrm{V}$) to ensure the full LISA sensitivity.
- Need for a **charge management system** (CMS) to keep the TM voltage under control.
- LPF successfully proved that this could be achieved with Hg UV-lamps.



But, why?

The **electrostatic force** on the TM (at *linear order*) is

$$F_x = \frac{Q_{TM}}{C_{tot}} \frac{dC_x}{dx} \Delta_x$$



The *two* main sources of **electrostatic force noise** are:

- Interaction of a charged TM with **noisy stray potentials** (*dominant*)

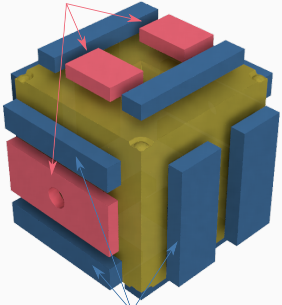
$$S_{F_x(\delta\Delta_x)} = \left[\frac{Q_{TM}}{C_{tot}} \frac{dC_x}{dx}\right]^2 S_{\Delta_x}$$

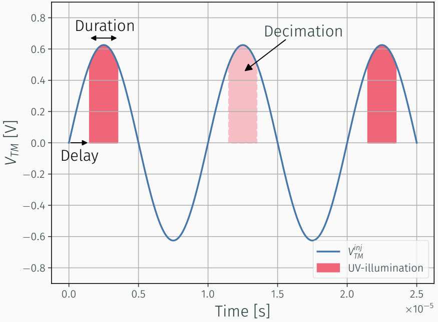
- Interaction of a **fluctuating TM charge** with DC stray potentials (*relevant at low-frequencies*)

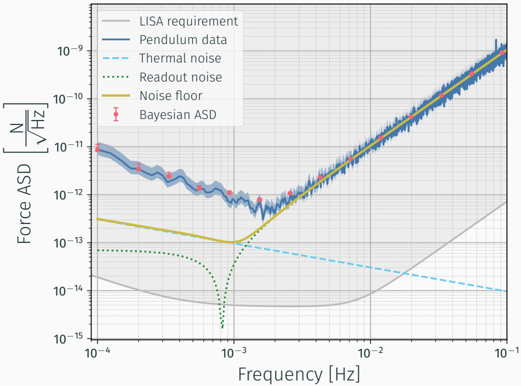
$$S_{F_x(\delta Q_{TM})} = S_{Q_{TM}} \left[\frac{1}{C_{tot}} \frac{dC_x}{dx} \Delta_x\right]^2$$

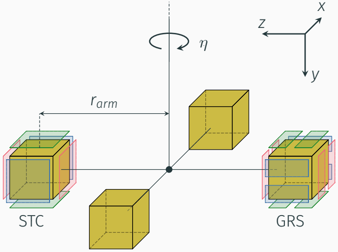
For LISA the current design aims to use **UV-LEDs**, with the following advantages:

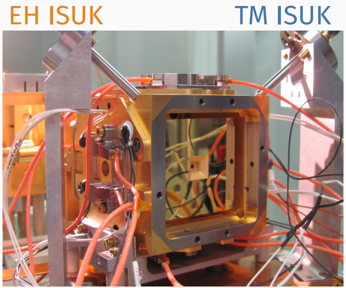
- Can be **synchronized** with the 100 *k*Hz TM bias (also improved redundancy).
- Weight and volume saving.
- More reliable and robust (longer lifetime).











Main features of our facility

Flight model replica of LPF GRS, copy of LPF FEE for actuation/sensing, ISUK positioned as in LPF.

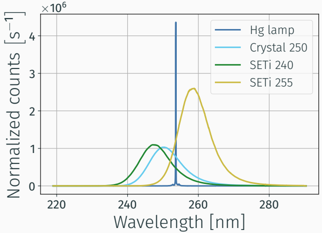
UV light sources and prototype CMD

Light sources

- LPF Hg-lamp replica
- SETi 255
- SETi 240
- Crystal 250

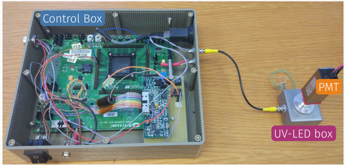
UV power measurement

- Si-Photodiode (*S1337-1010BQ*)
- PMT (*H6780-03*)
- Spectrometer (*AvaSpec-ULS2048XL-EVO*)

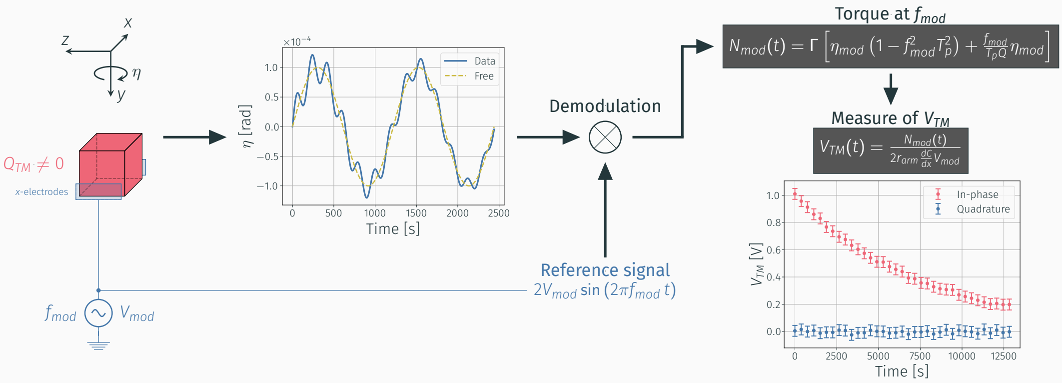


Charge Management Device

Prototype CMD provided by the INFN/Roma Tor Vergata group.



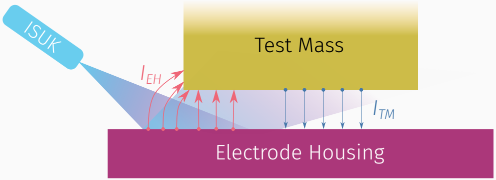
Apparent yield measurements

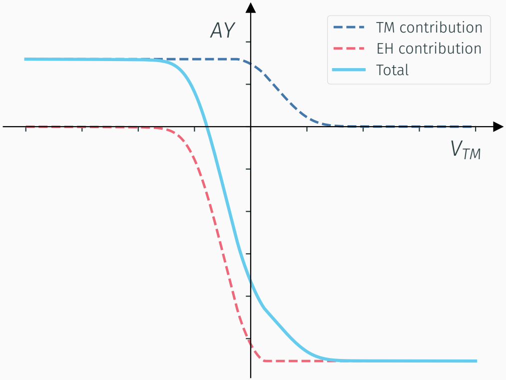


Apparent yield:

$$AY \equiv \frac{\#\,\text{charges}/s}{\#\,\text{photons}/s} = \frac{\frac{1}{e}\frac{dQ_{TM}}{dt}}{\frac{P_{UV}}{hf_{UV}}} = \frac{hf_{UV}}{eP_{UV}} C_{tot} \frac{dV_{TM}}{dt}$$

As the inner surfaces of the gravitational reference sensor (GRS) are *reflective*, a fraction of the incident UV-light is **absorbed** by the opposing surface.

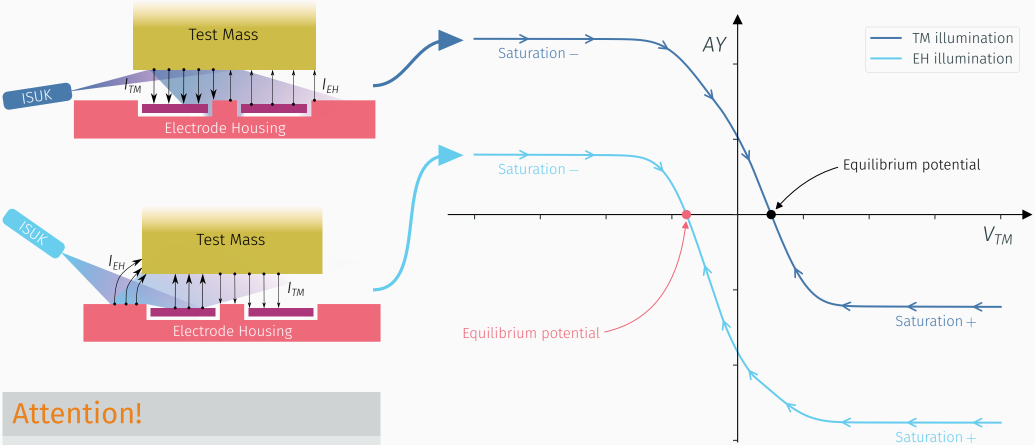




Attention!

The arrows indicate the direction of e^- motion!

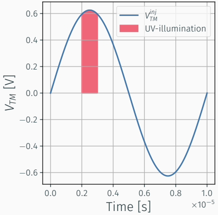
Differences for TM and EH illuminations

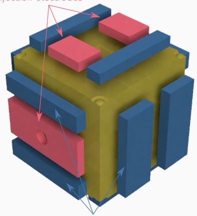


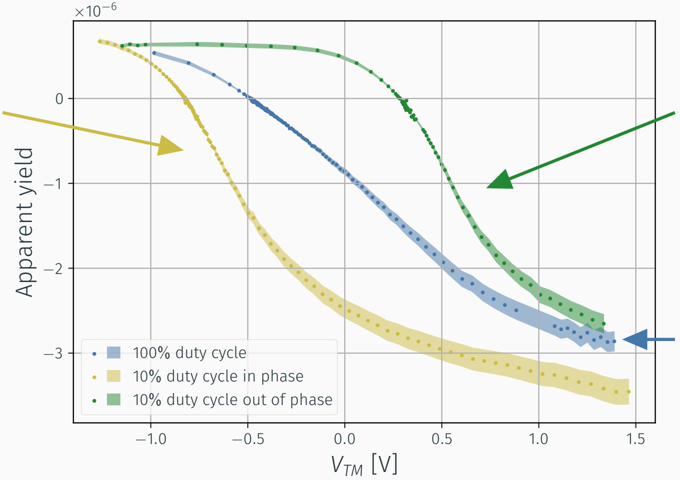
Attention!

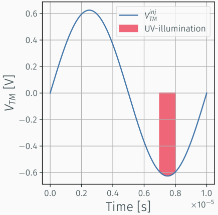
The arrows indicate the direction of e^- motion!

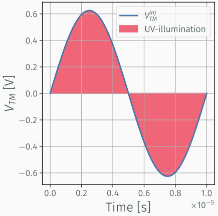
Measured apparent yield (Crystal 250, EH illumination)

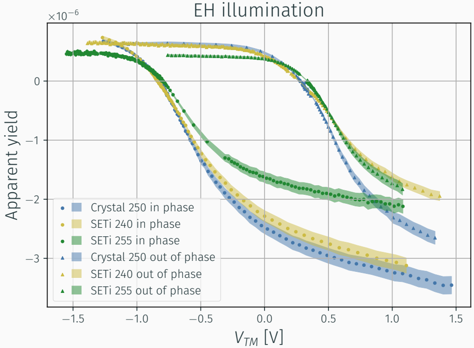


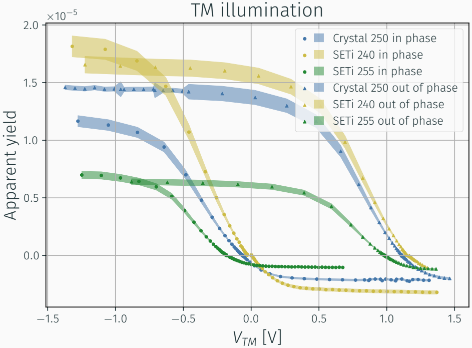












NB!

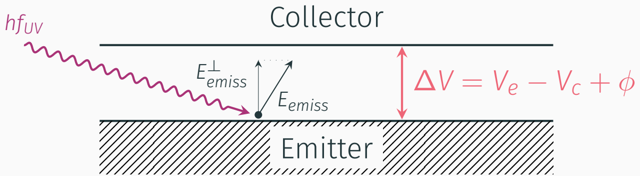
We had some issues regarding the power normalization!

The model is based on the follwing **assumptions**:

- **Idealized geometry**: EH and TM surfaces are plane parallel sheets.
- The electrons in the emitter are modeled as a free *Fermi gas*. The absorbed photon brings their normal kinetic energy to $E_0^\perp + hf_{UV}$.
- If $E_0^\perp + hf_{UV} > E_{F,e} + W_e$, there is a non-zero probability of being emitted with

$$E^\perp_{emiss} = E_0^\perp + hf_{UV} - W_e - E_{F,e}$$

- All emitted e^- with energy larger than the *potential barrier* ΔV contribute to the photocurrent (where ϕ is the contact potential).



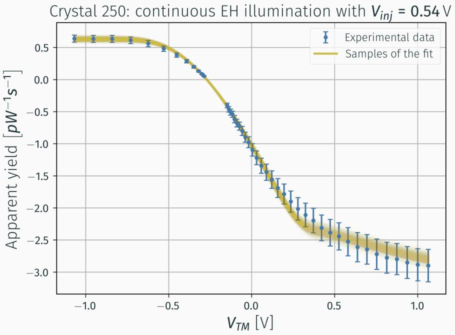
Fit of the data

The Bayesian fit obtained by sampling the following *Gaussian log-likelihood* with a **Hamiltonian Monte Carlo** algorithm (NUTS by the API PyMC3)

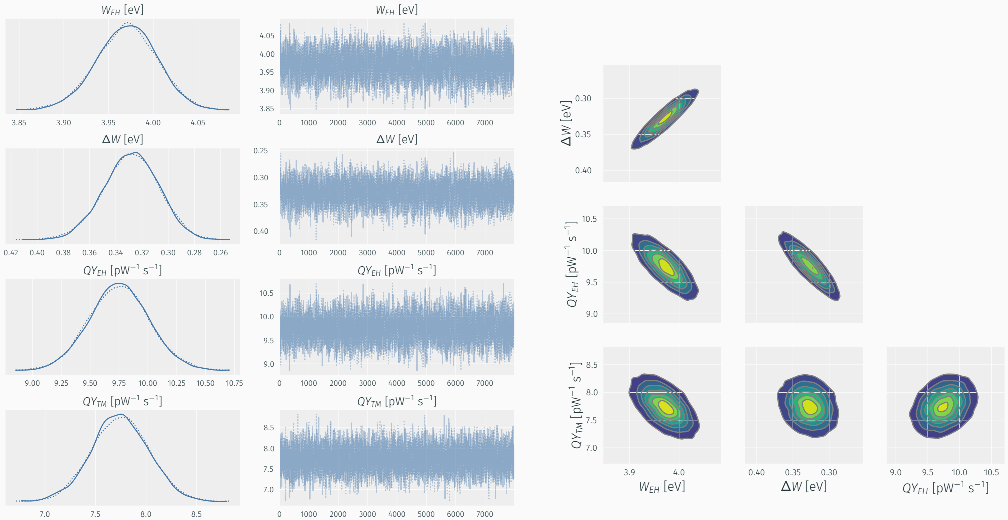
$$LL(\mathbf{y}|\boldsymbol{\theta}) = -\frac{1}{2}\sum_i \frac{[y_i - f(\boldsymbol{\theta}, x_i)]}{\sigma_i^2}$$

The fit parameters $\boldsymbol{\theta}$ are:

- The work function of EH (W_{EH})
- The difference of TM and EH work function ($\Delta W = W_{TM} - W_{EH}$)
- The quantum yield of EH (QY_{EH})
- The quantum yield of TM (QY_{TM})



Posterior distribution of fit parameters



Except for some anomalies, we experimentally proved the **advantages** of using UV-LEDs synchronized with the injection bias, such as of *tuning the TM voltage* and the *discharge rate* with the phase of the illumination.

We have a simple but effective model to interpret the data and extract relevant surface parameters (e.g. $W_{EH} = 3.97 \pm 0.03\,\text{eV}$ and $W_{TM} = 3.64 \pm 0.05\,\text{eV}$), which would be hard to measure otherwise.

Future steps

- Apply the fitting procedure to all the AY data.
- Improve our models to interpret the data (*FEM model* for photoelectrons trajectories and fields, accurate *mapping light absorption*).

Thank you for the attention!