Modeling the discharge properties for isolated test masses in gravitational reference sensors for fundamental space measurements

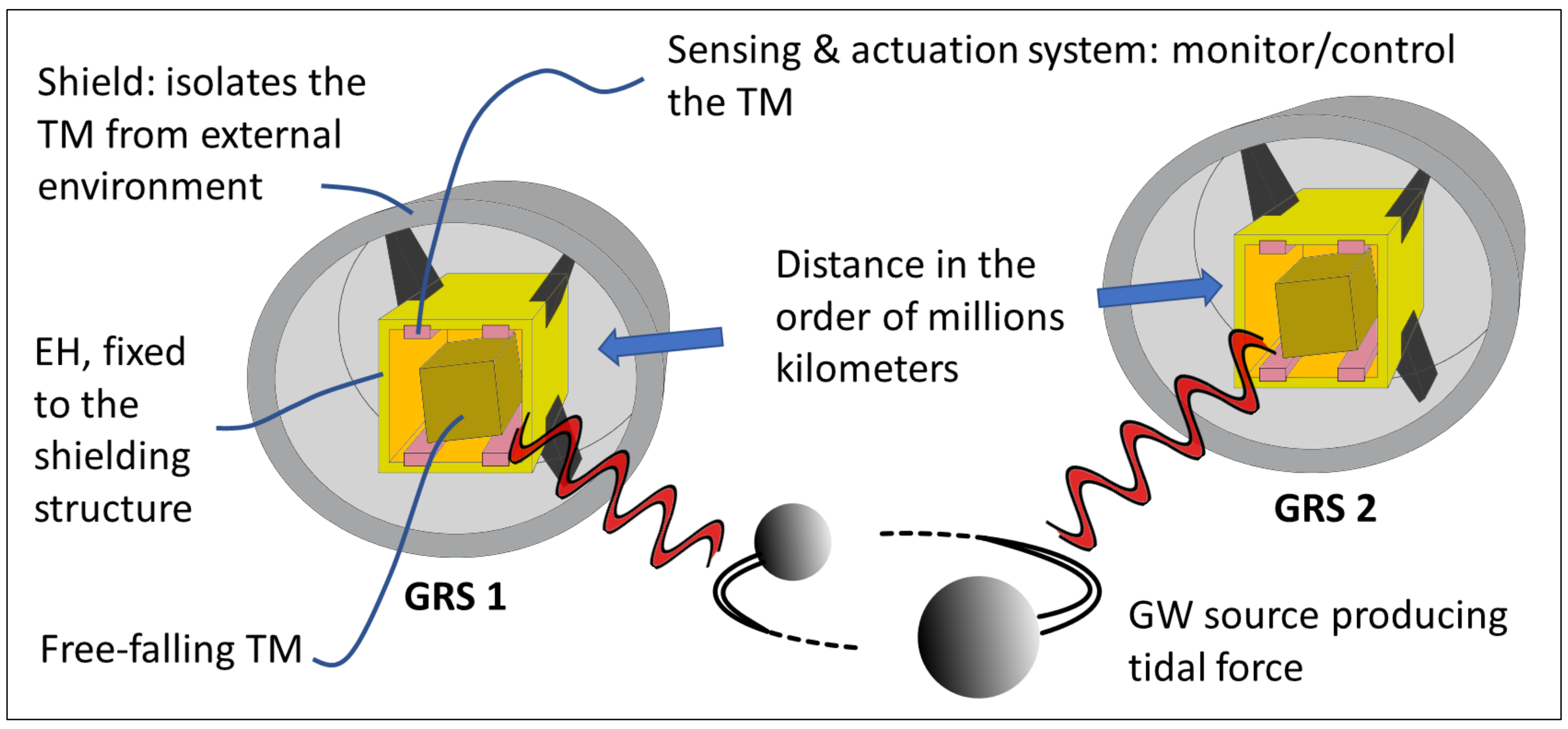
D. Vignotto[1], V. Ferroni[2]

1 – Dept. of Industrial Engineering, Univ. of Trento, Italy, davide.vignotto@unitn.it

2 – Dept. of Physics, Univ. of Trento, Italy, valerio.ferroni@unitn.it

Introduction: gravitational reference sensors in space

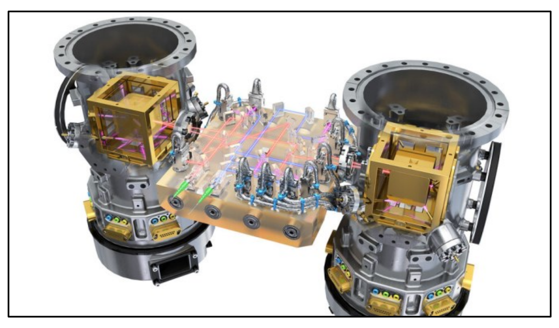
Principle behind *gravitational reference sensors* (GRSs): proof mass (TM), hosted inside an electrode housing (EH), in a free-falling trajectory, used as an inertial reference system [1].
GRSs are fundamental for precise measurements in space: gradiometry, small force experiments and gravitational wave (GW) detection [2].



Concept of gravitational waves detection: measure the strain distance between a couple of free-falling TMs.

Example of GRS: GP-B [3] and LISA Pathfinder [4].

Gravity Probe – B uses spherical proof masses.

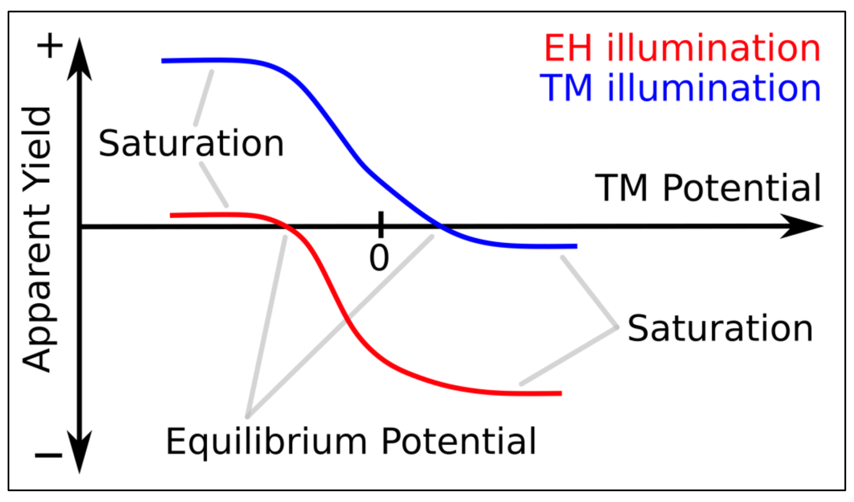


LISA Pathfinder includes two GRSs with cubic shaped TMs.

PROBLEM: in space, TMs are charged by high energetic particles. Coulomb/Lorentz forces, due to residual electromagnetic fields, perturb TMs motion. A TM charge control is needed [5].

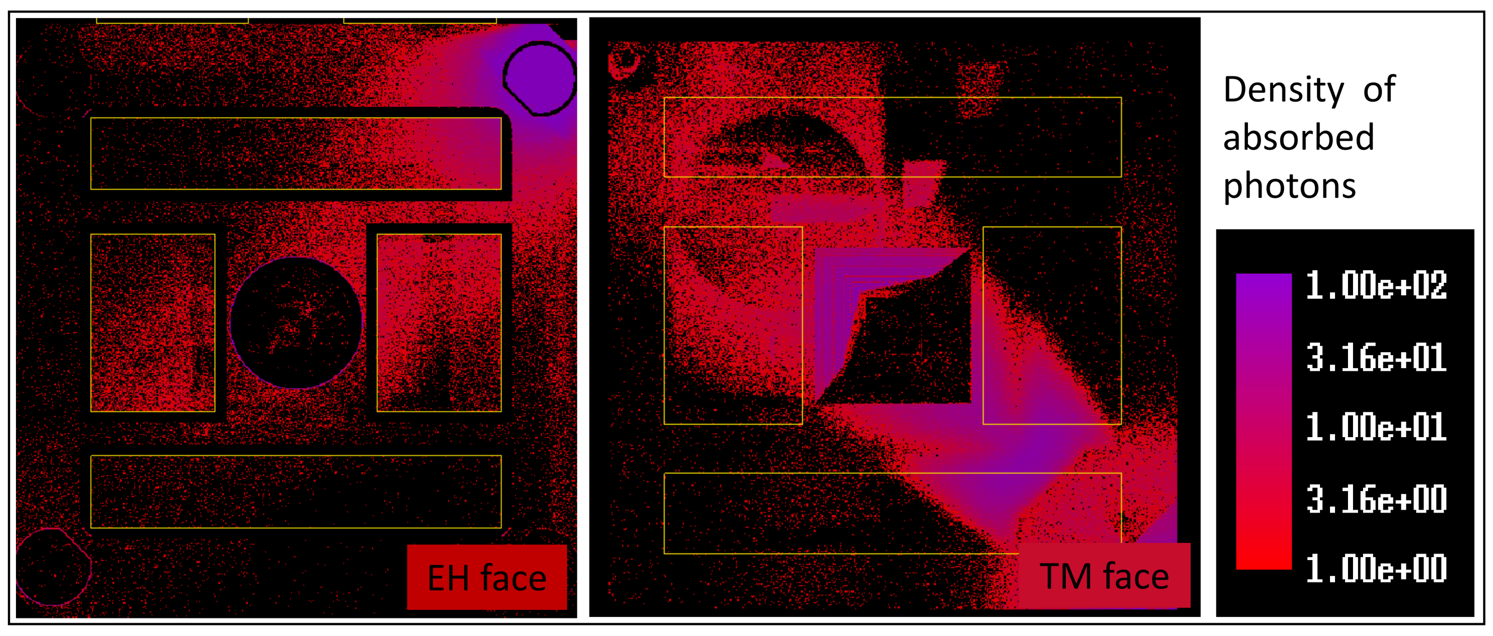
SOLUTION: contact-free charge management system (CMS) with ultraviolet (UV) driven photoelectric effect [6].

METHOD: the quite complex geometries of the GRS require a finite elements model (FEM) for a precise prediction of the TM discharge properties.
Those are fully represented by the apparent yield (AY) curves of the GRS.



GRS apparent yield: TM discharge prop.

2 GEANT4

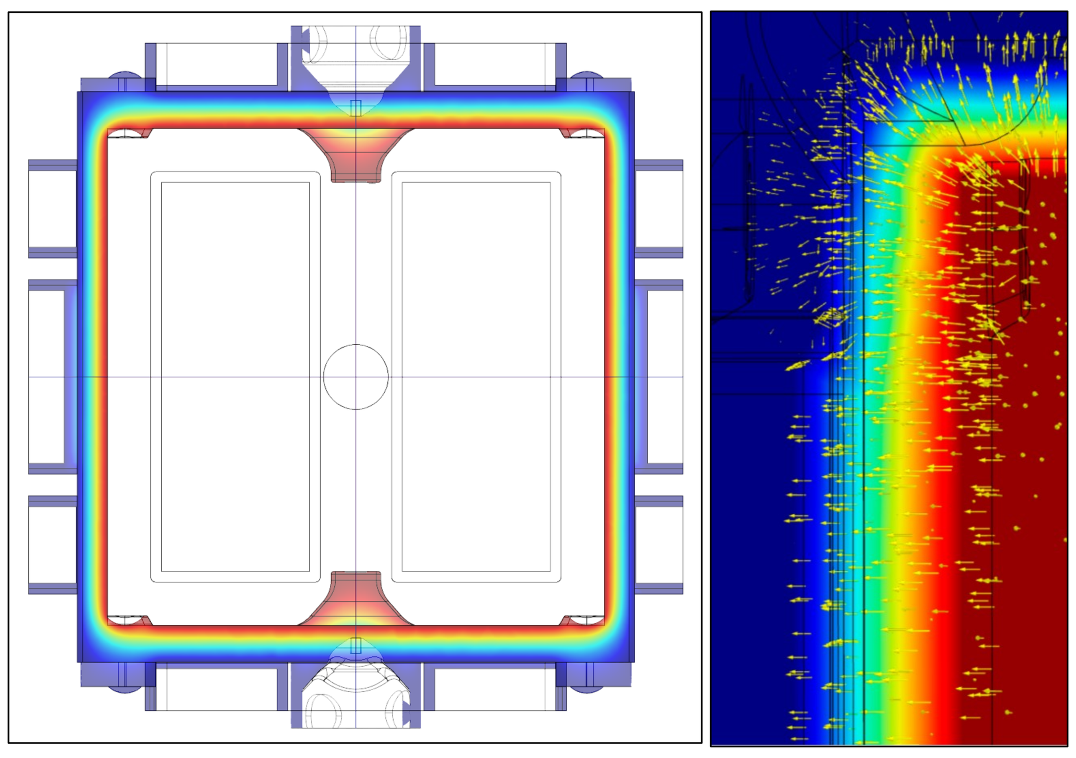


Absorption maps of UV light on GRS main surfaces.

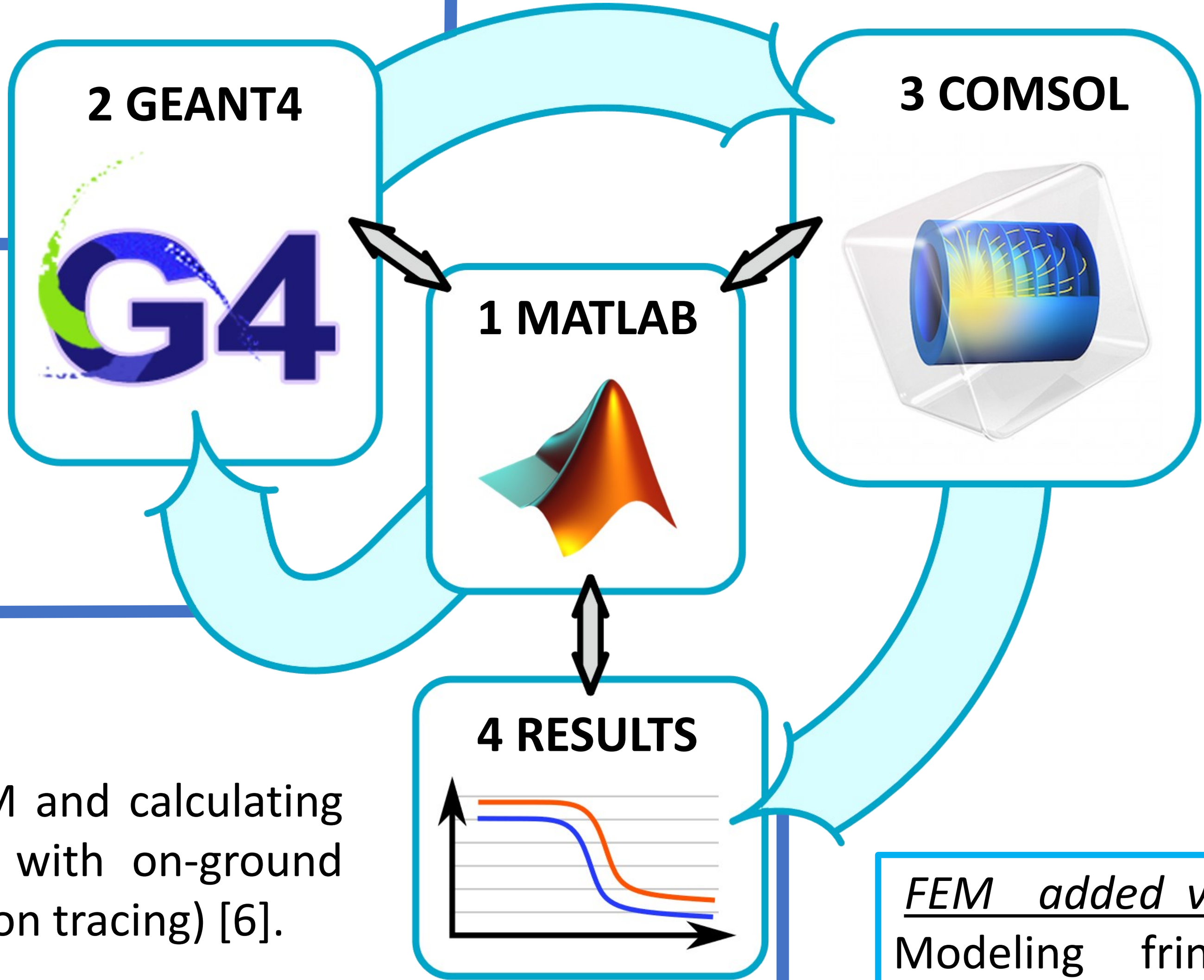
Propagating UV light inside the GRS. Calculating photoelectron emission properties (initial position and momentum).

3 COMSOL

Modeling the electrostatic field over the GRS complex geometrical features (this is important also for sensing and actuation calibration).
Tracing the photoelectrons along the electrostatic field in the space between the TM and the EH surfaces.

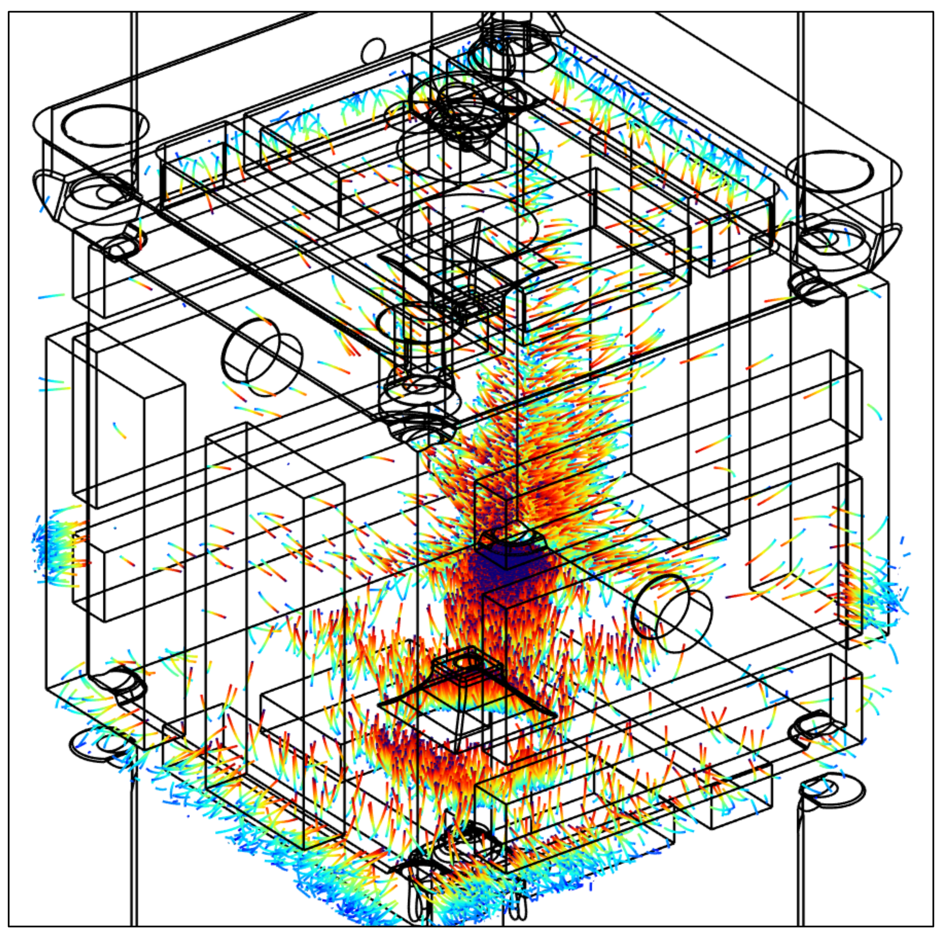


Left, electric potential inside the GRS. Right, detail near a TM vertex showing the electric field lines.



1 MATLAB

Interconnecting with GEANT4 and COMSOL to launch simulations, save the results and build AY curves. Case of study: *LISA Pathfinder GRS* [4].

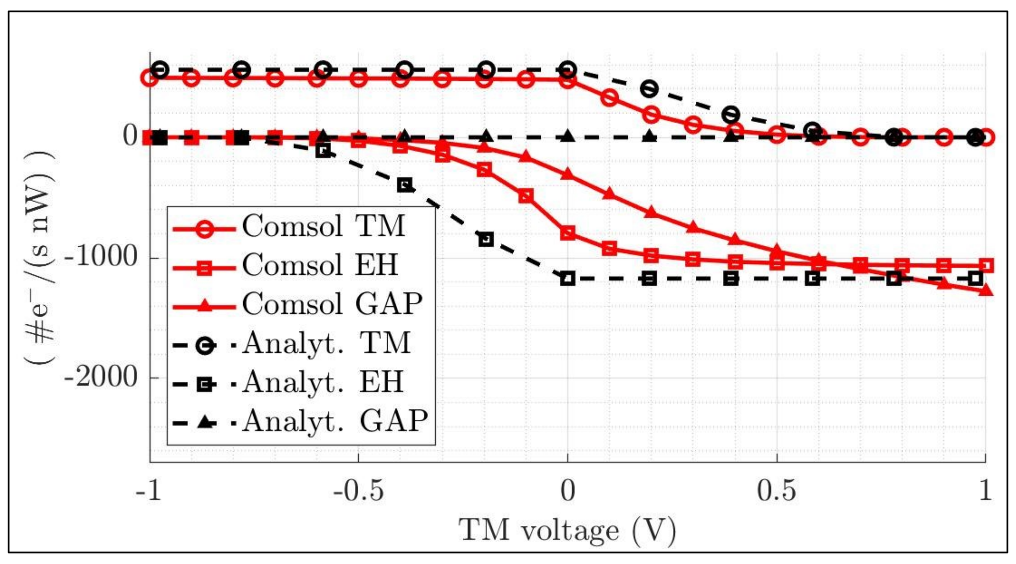


Screenshot of photoelectron trajectories inside the GRS. Light blue: slowest electrons; dark red: fastest electrons.

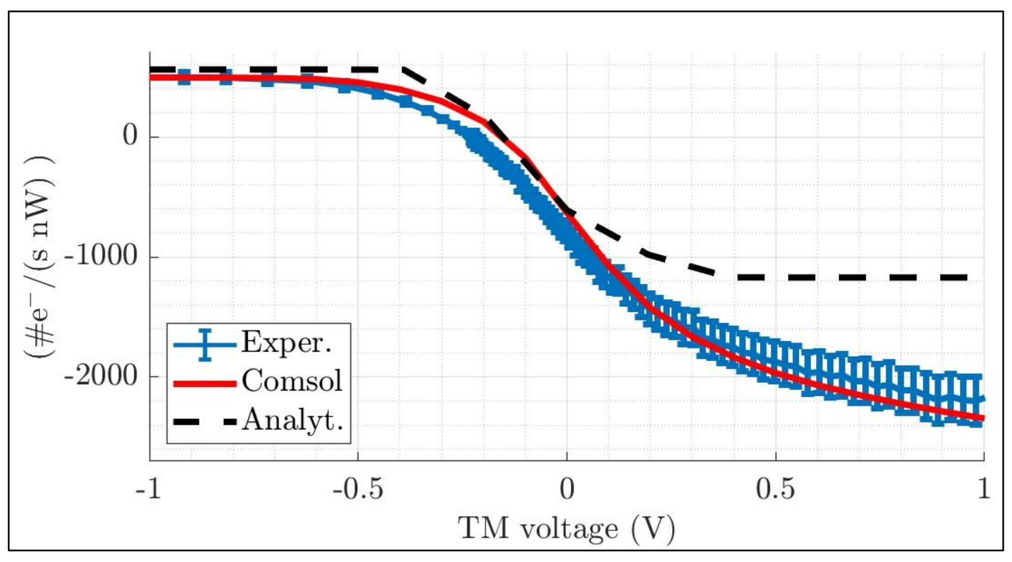
FEM added value
Modeling fringing fields that heavily affect the electrons trajectories.

4 RESULTS

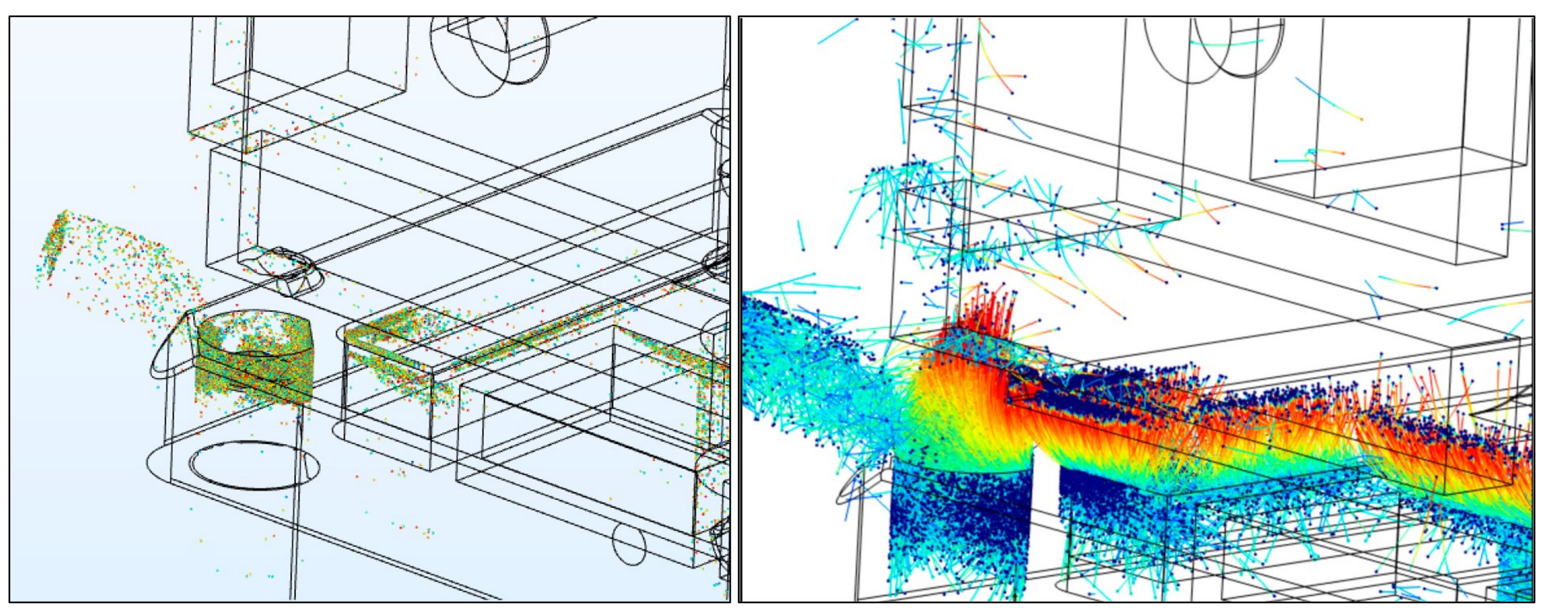
Counting the number of electrons reaching the TM and calculating the GRS apparent yield. Results are compared with on-ground testing data [4] and a 1D analytical model (no electron tracing) [6].



GRS apparent yield partials: contributions divided in TM, EH and GAP surfaces. The predominant GAP contribution is only accounted by the FEM model.



GRS apparent yield: analytical vs FEM vs experimental results. Analytical results underestimate AY at high TM voltage. FEM results match the real behaviour.



Largest part of the total photoelectrons is emitted from the numerous recesses (GAP) of the GRS. Left, emission points. Right, trajectories bent by the electric field.

The FEM is fundamental for modeling and predicting the TM discharge behaviour. Precise 3D representation of electric fields and tracing of electron trajectories is needed to account for all possible contributions.

1- I Triad. A satellite freed of all but gravitational forces. *Journal of Spacecraft*, 11(9), 1974.

2- K Danzmann et al. LISA Laser Interferometer Space Antenna. In *ESA L3 Mission Proposal*, 2017.

3- CWF Everitt et al. The gravity probe b test of general relativity. *Classical and Quantum Gravity*, 32(22):224001, 2015.

4- Michele Armano et al. Sub-femto-g free fall for space-based gravitational wave observatories: LISA Pathfinder results. *Physical review letters*, 116(23):231101, 2016.

5- H.M. Araújo, P. Wass, D. Shaul, G. Rochester, and T.J. Sumner. Detailed calculation of test-mass charging in the LISA mission. *Astroparticle Physics*, 22(5):451–469, 2005.

6- Michele Armano, H Audley, J Baird, P Binetruy, M Born, D Bortoluzzi, E Castelli, A Cavalleri, A Cesarini, AM Cruise, et al. Precision charge control for isolated free-falling test masses: LISA Pathfinder results. *Physical Review D*, 98(6):062001, 2018.