TM Charging Toolkit

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Preparato da: *Prepared by:*	Toolkit Team		
Approvato da: *Approved by:*	Ferroni V. (Univ. Trento)	2023.11.29 18:45:19 +01'00'	
	Grimani C. (Univ. Urb.)	Date: 2023.11.29 19:33:17 +01'00'	
	Sarra P. (OHBI – SE)	2023.11.30 08:33:29 +01'00'	
	Battini F. (OHBI – PA)	2023.11.30 11:26:01 +01'00'	
	Parrella G. (OHBI – CC)	2023.11.30 13:37:22 +01'00'	
Applicazione autorizzata da: *Application authorized by:*	Lorenzi P. (OHBI – PM)	2023.11.30 11:22:20 +01'00'	
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1. SCOPE

The document reports the main finding of the Contract discussing the context and the work done by the Team and highlighting the main findings.

This document is provided for the FAR milestone of the ESA Contract No. 4000133571/20/NL/CRS “Test Mass Charging Toolkit and LPF Lessons Learned”. This document includes the following contractual deliverable to ESA:

- ESR Executive Summary Report.

2. APPLICABLE AND REFERENCE DOCUMENTS

2.1 APPLICABLE DOCUMENTS

The contractual applicable documents are listed in Table 2-1.

AD	Doc. No.	Issue Rev.	Title
[AD01]	ECSS-E-ST-10-04C		Space environment http://ecss.nl/standard/ecss-e-st-1004c-space-environment/
[AD02]	ECSS-E-ST-40C		Software http://ecss.nl/standard/ecss-e-st-40csoftwaregeneral-requirements/
[AD03]	ECSS-E-HB-40A		Software Engineering Handbook http://ecss.nl/hbstms/ecssehb-40a-software-engineering-handbook-11-december-2013/
[AD04]			GEANT4 documentation, https://geant4.web.cern.ch/support/user_documentation
[AD05]			GRAS documentation, http://space-env.esa.int/index.php/geant4-radiationanalysis-for-space.html
[AD06]	AO10081-ws00pe		Statement of Work Test mass charging toolkit and LPF lessons learned

Table 2-1 Applicable Documents

2.2 REFERENCE DOCUMENTS

The reference documents are listed in Table 2-2.

RD	Doc. No.	Issue Rev.	Titolo
[RD01]			C. Grimani et al., Classical and Quantum Gravity 21 (5), S629, 2004
[RD02]			H. Vocca et al., Classical and Quantum Gravity 21 (5), S665, 2004
[RD03]			C. Grimani et al., Classical and Quantum Gravity 22 (10), S327, 2005
[RD04]			H. Vocca et al., Classical and Quantum Gravity 22 (10), S319, 2005
[RD05]			C. Grimani et al., CQG, 32, 035001, 2015

RD	Doc. No.	Issue Rev.	Titolo
[RD06]			P. J. Wass et al. CQG 22, S311, 2005
[RD07]			D. N. A. Shaul et al., CQG 22, S297, 2005
[RD08]			H. M. Araujo et al., Astroparticle Physics 22, 451, 2005
[RD09]			F. Antonucci et al., Phys. Rev. Lett. 108 181101 2012
[RD10]			M. Armano et al., Physical review letters 116 (23), 231101, 2016
[RD11]			M. Armano et al., Physical review letters 120 (6), 061101, 2018
[RD12]			M. Armano et al., Physical review letters 118 (17), 171101, 2017
[RD13]			M. Armano et al., Physical Review D 98 (6), 062001, 2018
[RD14]			M. Armano et al., Physical Review D 107 (6), 062007, 2023
[RD15]			D. Sakata et al. JAP 120 244901, 2016
[RD16]			F. A. Cucinotta et al. in: "Two-Center Effects in Ion–Atom Collisions: A Symposium in Honor of M. Eugene Rudd" ed. T. J. Gay and A. F. Starace, AIP conference proceedings 362; AIP, Woodbury, New York, page 245-265, 1996
[RD17]			S. Taioli et al. CQG 40, 075001, 2023
[RD18]			C. Grimani et al., A&A, 666, A38, 2022
[RD19]			C. Grimani et al.; CQG, 38 (4), 045013, 2020
[RD20]			C. Grimani et al. A&A, 656, A15, 2021
[RD21]			L. J. Gleeson. and W. I. Axford, ApJ, 154, 1011, 1968
[RD22]			M. Armano et al., ApJ, 854, 113, 2018
[RD23]			M. Armano et al., ApJ, 874, 167, 2019
[RD24]			M Villani et al., Experimental Astronomy 56 (1), 1-30, 2023
[RD25]			O. Adriani et al., ApJ, 742, 102, 2011
[RD26]			C. Grimani et al., JPCS, 409, 2159, 2013

RD	Doc. No.	Issue Rev.	Titolo
[RD27]	TMCTK-MA-OHBI-001	4	TM Charging Simulation Software User Manual
[RD28]	TMCTK-RP-OHBI-001	1	TM Charging Simulation Final Report
[RD29]			P. Amaro-Seoane et al. arXiv:1702.00786, 2017

Table 2-2 Reference Documents

3. TERMS, DEFINITIONS AND ABBREVIATED TERMS

AD	Applicable Document
API	Application Programming Interface
CDR	Critical Design Review
DDF	Design Definition File
DJF	Design Justification File
ESA	European Space Agency
ESR	Executive Summary Report ESTEC
ESTEC	European Space research and Technology centre
ETDD	Effects Tool Design Document
FAR	Final Acceptance Review
FLUKA	FLUktuierende KAskade
GCR	Galactic Cosmic Rays
GEMAT	Geant4-based Microdosimetry Analysis Tool
GRAS	Geant4 Radiation Analysis for Space GSP
GRS	Gravitational Reference Sensor
GSP	General Studies Programme
GUI	Graphical User Interface
IDD	Interface Design Document
IMF	Interplanetary magnetic field
KOM	Kick-off Meeting
LISA	Laser Interferometer Space Antenna
LPF	LISA Pathfinder
PDR	Preliminary Design Review
PM	Progress Meeting
PR	Progress Report
RD	Reference Document
SEP	Solar Energetic Particles
SDD	System Design Document
SoW	Statement of Work
SPE	Solar particle event
SPENVIS	SPace ENVironment Information System
SRR	System Requirements Review
SUM	Software User Manual
SW	Software
TN	Technical Note
TRR	Test Readiness Review
TS	Technical Specification

4. INTRODUCTION

The success of the LISA Pathfinder mission in providing the proof that test masses (TMs) can be put in free fall in orbit following a geodesic motion down to 1 femto-g level in the [0.1–20] mHz frequency band, paved the way for the realization of the LISA gravitational wave observatory in space. The isolated TM of LISA Pathfinder charged up due to the action of particles of galactic origin; due to the abundance of protons among the species composing the particle flux hitting the spacecraft, positive charges accumulated on the TM with a rate ranging between 20 to 40 e/s during the mission. In the year and half mission period no solar energetic particle events occurred, whereas a few transients in the galactic cosmic ray flux were observed. Due to the presence of native local stray electric fields, Coulomb noisy[1] forces perturb the TM free-fall motion up to 0.1 femto-g at most. This force noise level was achieved in LISA Pathfinder: I) by providing local electric field compensation within 5 mV of potential difference between TM and any one of the electrodes, and II) the usage of charge control devices able to maintain the TM charge limited between ±140 mV (±5 pC considering the TM auto-capacitance).

LISA experiences the same problem of LISA Pathfinder with Coulomb force noise. Thanks to lessons learned with LISA Pathfinder, we are now aware that early time Monte Carlo simulations of the charging process sensibly underestimated the shot-noise term of the charging process.

The statement of work of this ITT [AD06] arises from the need to reconcile the results of LISA Pathfinder in-flight charging measurements with Monte Carlo simulation outcomes. The contents of the statement of work were aimed at developing a new toolkit based on the GEANT4 framework for the estimate of the effect of the low-energy electromagnetic physics on TM charging that were not included in previous Monte Carlo simulations. In addition, the interest was also to take into account the role of interplanetary processes in modulating the galactic cosmic-ray (GCR) flux and to study the role of SEP to disentangle the TM charging under pseudo stationary conditions and during transients. Ultimately, the impact of the charging process on the LISA observatory sensitivity and science data analysis had to be evaluated.

[1] The noisy characteristics of the Coulomb forces is due to the stray field fluctuation and due to the shot noise which charge deposition on the TM occur with

5. PARTICLE SPACE ENVIRONMENT AND METHODS

The Team under Contract for this ITT is led by OHBI with P. Sarra, P. Lorenzi, F. Battini in collaboration of University of Trento with V. Ferroni, F. Dimiccoli and W.J. Weber, and University of Urbino with C. Grimani, M. Villani and M. Fabi. The work provided by the Team followed closely the tasks proposed by ESA in [AD06]: all the milestones of the Contract were successfully passed. The team got to the Final Acceptance Review with the toolkit software ready to use, verified and validated in all its parts and in end-to-end simulations. All the required technical documentation was completed.

The Team worked mostly in remote, by organizing and attending the needed progress meetings and the Contract reviews with ESA.

The Team activities focused on the following main areas:

1. Review of the LISA Pathfinder TM charging studies and experimental measurements

For the proposal of this ITT the Team documented its expertise about the problems associated with the environmental charging of the free-falling TMs used for space applications such as gravitational reference sensors and end mirrors of interferometric gravitational wave observatories. As part of the LISA Pathfinder developing and operational collaboration, and of the LISA collaboration, the Team was author of several publications regarding Monte Carlo simulations of TM charging in space [RD01]-[RD08], and charge-induced disturbances on the free-falling TM motions. These studies were carried out for both on ground facilities and in space with LISA Pathfinder [RD09]-[RD14]. That experience allowed the Team to define the requirements for the present simulations, in particular those related to the low electromagnetic physics with respect to the past version of the Monte Carlo software, and the functions of the toolkit requested by ESA.

2. Study of the low-energy electromagnetic processes: low-energy ionization and back-scattering, quantum diffraction

Extensive studies to assess the importance of keV and sub-keV electromagnetic processes affecting the LISA Pathfinder and LISA TM charging have been carried out at the University of Urbino Carlo Bo to bridge the gap characterizing the FLUKA electron, positron and photon propagation cut-off in matter limited to 1 keV. We have developed a module called LEI that implements low-energy electromagnetic processes to be interfaced with FLUKA in the outer 150 nm of gold of TM and electrode housing.

Low-energy ionization was found to be of paramount importance. In FLUKA/LEI the ionization is implemented in two different ways depending on the particle species: we have used the Sakata et al. [RD15] cross section for electrons and positrons and the Cucinotta et al. formula [RD16] for all other kind of particles.

We have also found that electron quantum diffraction plays an important role below 100 eV. We have calculated the probabilities that an electron has to be reflected at a particular angle when impinges on a gold crystal depending on its energy and angle of incidence with respect to the normal to the gold surface. The contribution from the three Bragg's planes was considered. The results of the calculations were implemented in FLUKA/LEI as a yield.

Another important process implemented in LEI is the electron kinetic emission: the emission and the backscattering of electrons from a surface bombarded by low-energy (approx. keV) electrons. It is implemented in LEI as a yield according to the calculations by Taioli et al. [RD17] .

The inclusion of these processes in FLUKA/LEI has improved sensibly the agreement of Monte Carlo simulations with LISA Pathfinder measurement of the TM charging noise [RD18]. These results guided us towards the adoption of GEANT4-DNA v11 which already included part of the processes mentioned above in gold.

Low-energy processes involving photons such as bremsstrahlung radiation were found to be of negligible importance and were not implemented [RD19] .

3. Galactic cosmic rays and solar energetic particles: input flux database and model

A database of cosmic-ray and solar particle fluxes adopted for the Monte Carlo simulations was provided. The GCR flux observed in the inner heliosphere shows time, energy, charge and space dependence [RD20]. Long-term variations associated with the 11-year solar cycle and the 22-year polarity reversal of the Global Solar Magnetic Field (GSMF) have been taken into account. These long-term modulations are due to the particle propagation from the interstellar medium to the point of observations against the outward motion of the solar wind and embedded magnetic field. LISA is expected to be in space during a period of positive polarity of the GSMF (after 2035), as it was the case for LISA Pathfinder (2015-2017). Under these conditions, the model by Gleeson and Axford [RD21] can be used to take into account the effects of long-term GCR flux modulation (see for details Armano et al. [RD22]). For the GCR short-term variations, associated with the passage of high-speed solar wind streams (recurrent variations) and interplanetary counterparts of coronal mass ejections (non-recurrent variations), we preferred to consider real measurements instead of models since, on the basis of several and precious lessons learned about the interplanetary physics of cosmic rays with LISA Pathfinder [RD22] and [RD23], we observed that the response of the cosmic-ray flux at the passage of interplanetary structures does not primarily depends on the characteristics of these structures but on their interplay. Two structures very similar modulate the GCR flux differently, depending on the particle flux being already depressed or not by the passage of other structures [RD24]. As an example, we show in Figure 5-1 the observations carried out with the LISA Pathfinder radiation monitor of the GCR flux variations and the associated interplanetary structures during the Bartel's rotation 2496.

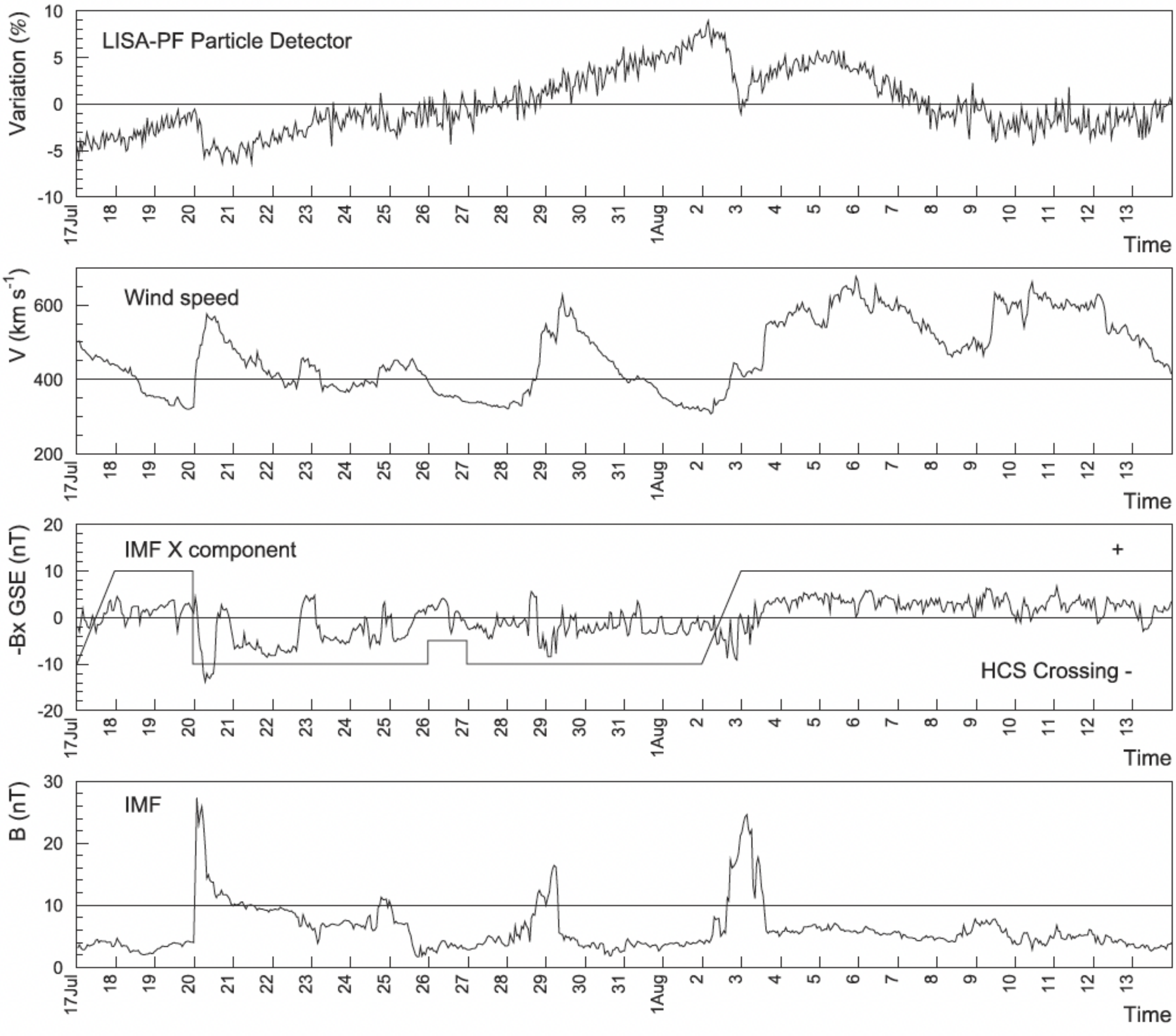

Figure 5-1 Top panel: GCR variations during the months of July and August 2016 observed with LISA Pathfinder in the first Lagrangian point (L1). In the bottom panels we show for comparison the solar wind speed, the x component of the interplanetary magnetic field in GSE coordinates and its intensity gathered with the NASA ACE mission also orbiting around L1 at the time of LISA Pathfinder was in space. On July 20th and August 2rd, two Forbush decreases are visible. The recovery phase of the second Forbush decrease was impeded by two overcoming high-speed solar wind streams [RD22].

Also for the solar energetic particle (SEP) fluxes, we reported the evolution of the measured proton (99% of the total bulk of particles) energy differential flux observed during the onset, peak and decay phases of events of different intensity. The observed spatial distributions of protons during the event dynamics were also indicated [RD25] and [RD29]. It is worthwhile to recall that particles of different energies will reach the LISA spacecraft at different times, depending on the magnetic connection between the spacecraft and the active region from which the coronal mass ejection originates (assuming particle shock acceleration, typical of gradual events, since the LISA TM charging will not be affected by particles below 50 MeV associated with impulsive events).

4. Test-mass charging toolkit: GEANT4 Monte Carlo simulations and charge-induced force impact on test-mass free-fall motion

The toolkit was built on a modular basis: a Monte Carlo module and an analysis module. The first one performs the Monte Carlo simulations of the TM charging with a predefined geometry and for several predefined input fluxes representative of GCR composition under steady state and during transients. The toolkit allows the user to customize both geometry and input fluxes. That is an important feature that makes the toolkit flexible for studying different mission configurations.

The results of the Monte Carlo simulations are presented in the form of timeseries of charge deposits on the TM and charge histograms such as the one shown in Figure 5-2.

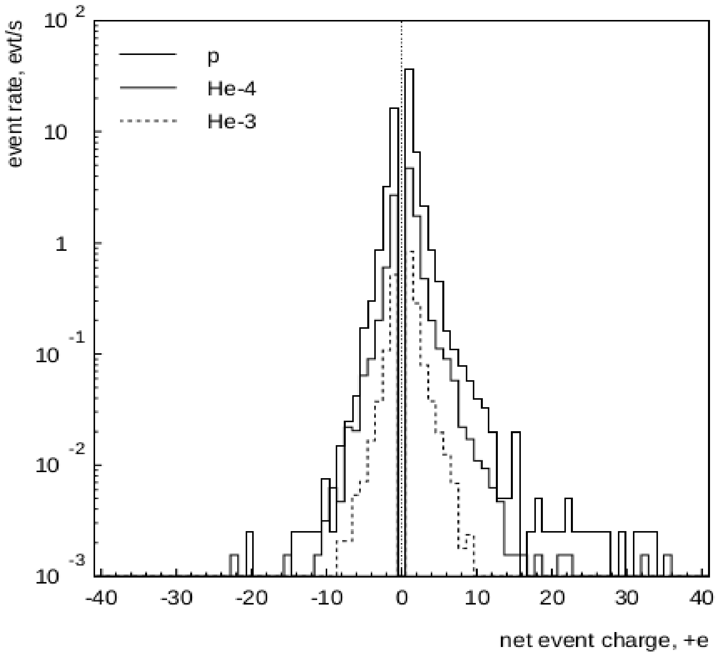

Figure 5-2 TM Charge deposit occurrence histogram for Proton and Helium under solar minimum condition.

The outcomes of the Monte Carlo simulations are fed to the analysis module to simulate the timeseries of the accumulated charge on the TM for a user selected period of time. These timeseries represent the actual charging process result that one would measure on the TM when a particle flux incident on the spacecraft is selected. With a given set of parameters representing the electrostatic configuration of the TM inside the electrode housing, the module calculates the charge-induced force on the TM. Eventually, the calculation of the signal to noise ratio is also provided for a given sensitivity curve.

6. RESULTS

In the following we report the simulation results obtained with our toolkit based on GEANT4-DNA (v.11) on a simplified geometry of the LISA spacecraft with matter uniformly distributed in shells of different thickness for a total grammage of 16 g cm^{-2} surrounding two 150 nm layers of gold and the gold TM. The geometry is shown in Figure 6-1.

We first consider the simulation of the TM charging due to the GCR flux in two extreme conditions of solar modulation, namely solar maximum and solar minimum. We report the average rate, λ_{NET}, of elementary charges deposited on the TM and the so-called effective charging rate λ_{EFF} which is directly proportional to the charge (q) power spectral density. The input fluxes are reported in [RD27], the Monte Carlo simulation results are shown in Table 3. More case studies are described [RD28].

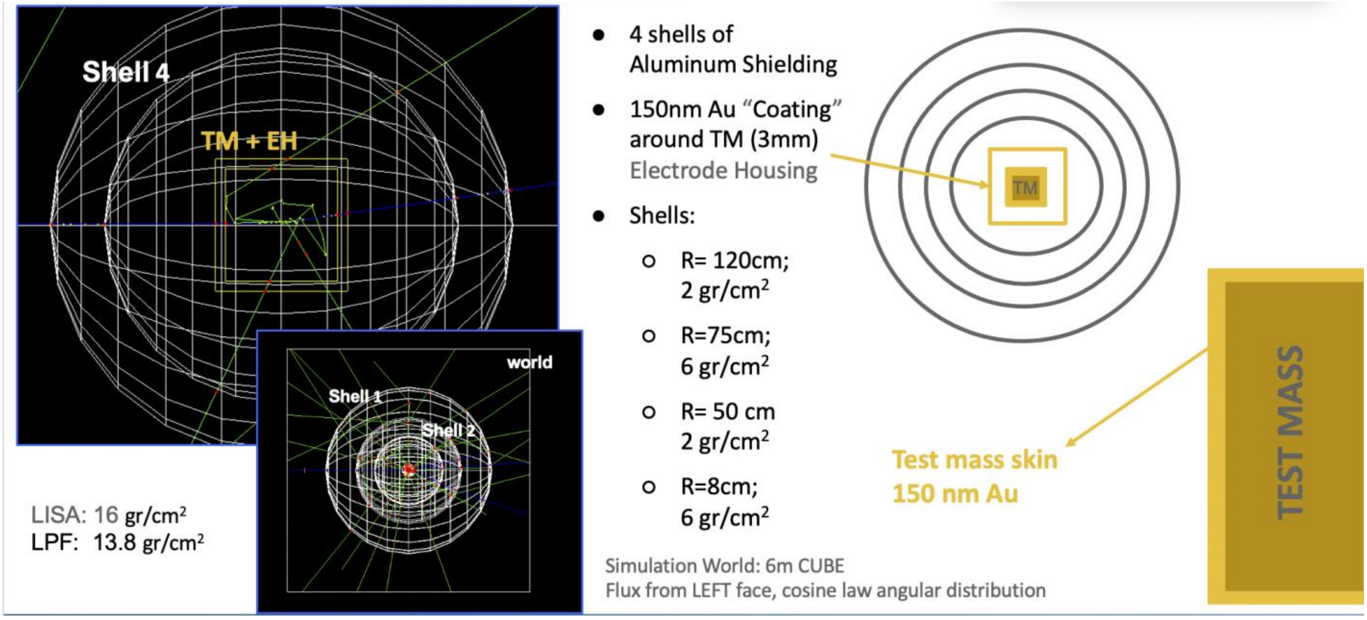

Figure 6-1 Simplified Geometry for the GEANT4-DNA simulations

Particles	Solar Minimum (Φ= 200 MV/c)		Solar Maximum (Φ= 1200 MV/c)	
	λ_{NET} $[s^{-1}]$	λ_{EFF} $[s^{-1}]$	λ_{NET} $[s^{-1}]$	λ_{EFF} $[s^{-1}]$
Protons	51.3	384	4.3	118
He3 +H4	4.3	79	1	47
Electrons	-0.4	59	-0.1	12
C	0.3	11.6	0.4	14
O	0.4	16.1	0.3	16.1
Fe	0.1	76	0.1	22
Total	56	626	6	229

Table 3 LISA TM charging simulation for solar maximum and solar minimum obtained with GEANT4-DNA v11

The main function of the toolkit is the capability to calculate the effects of the charging process on the free-falling TM motion and on the sensitivity of the LISA gravitational wave observatory. In the following we report the results of the analysis of a SEP event. We consider here the SEP event observed by the PAMELA satellite experiment on December 13, 2006. This is an interesting case of a medium-strong event that may likely occur during the LISA mission lifetime of 10 years. The input fluxes are reported in [RD27]. In *Figure 6-2* we show the timeline of the TM charge rate during the SEP event; *Figure 6-3* reports the evolution of the deposited charge on the TM, *Figure 6-4* the charge-induced force signal acting on the TM due to the Coulomb interaction between the TM charge and the native stray electric fields surrounding the TM.

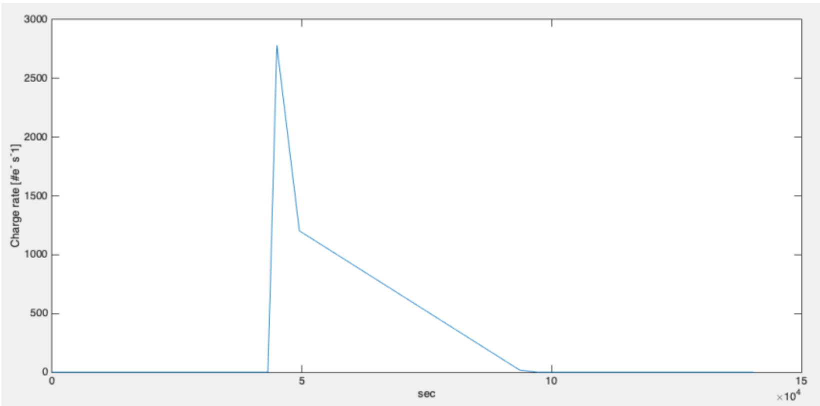

Figure 6-2 TM charge rate signal from the SEP event

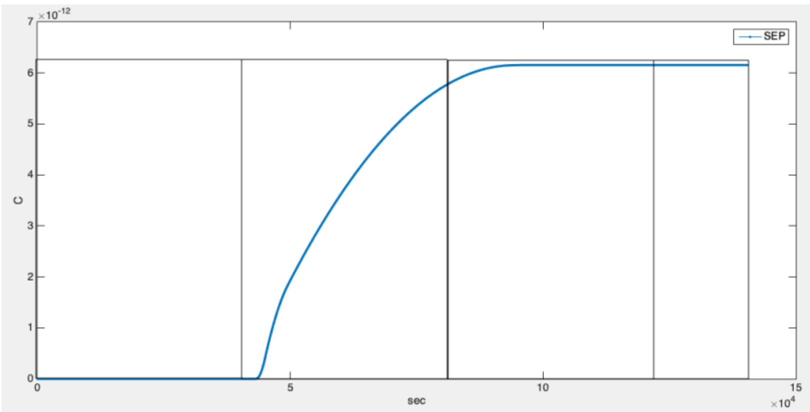

Figure 6-3 SEP TM charge timeseries. In evidence the windows for the spectral analysis

On the basis of observations, these stray electric fields, expressed in terms of a potential Δ_x, the equivalent potential difference, are uniformly distributed in the range of $5 - 100\ mV$. Assuming for LISA the amplitude spectral density of the force sensitivity as shown in *Figure 6-5*, the Signal to Noise ratio of this charge-induced force signal has been evaluated to be of the order of 20. We note that that is a significant non-gravitational force event visible on the LISA science data to be disentangled from gravitational wave data.

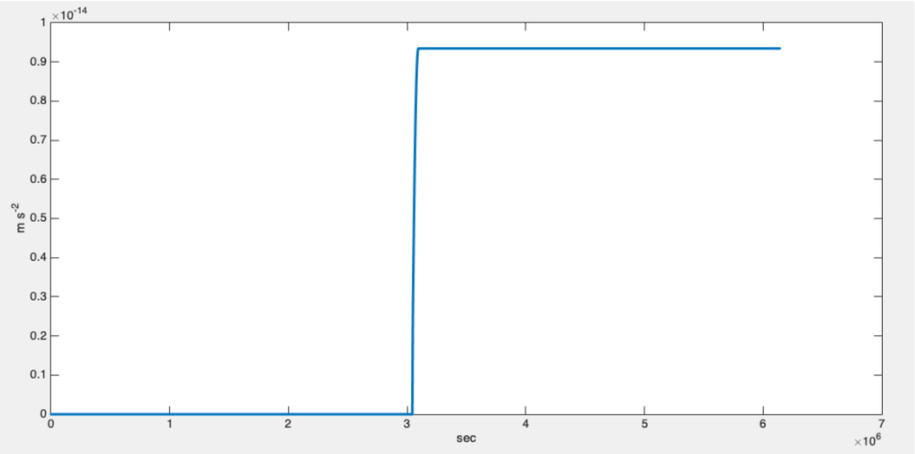

Figure 6-4 SEP TM charge-induced force timeseries

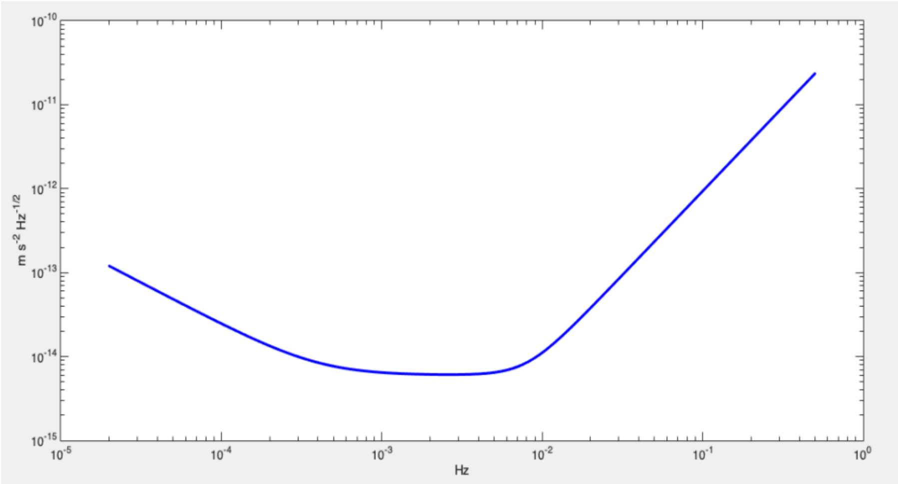

Figure 6-5 Proposed force sensitivity for the LISA gravitational wave observatory [RD29]

7. CONCLUSIONS

The toolkit delivered for this ITT allows for an end-to-end evaluation of the TM charging process in limiting the sensitivity of the LISA mission within the science band. Moreover, the toolkit is a key resource for an informed data analysis to disentangle the charge-induced force signals from gravitational ones. The toolkit adopts for the Monte Carlo simulation GEANT4-DNA V11 that allows for electron propagation in gold down to 10 eV.

The low-energy electrons have been found to play a major role in charging the TMs during the LISA Pathfinder mission. Taking into account the low-energy electrons constitutes a step forward in the Monte Carlo simulation of the TM charging for LISA. Another step forward, with respect to past studies about the TM charging, is the inclusion of the estimate of charge-induced forces on the TM motion and on the LISA sensitivity. As a result, we had the possibility to study the effects of transient charging events, in particular SEPs and Forbush decreases.