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Interaction Study of Energetic Protons and Electrons with the Vacuum Ultra Violet Source used in the Complex Irradiation Facility

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Interaction Study of Energetic Protons and Electrons with the Vacuum Ultra Violet Source used in the Complex Irradiation Facility

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Abstract. *Context:* One important factor to be considered for space missions is the radiation environment. It is composed of energetic particles, such as protons, electrons and ions, and electromagnetic radiation, photons ranging from Vacuum Ultra Violet (VUV) to Far Infrared (FIR). Each of these radiation sources have an unique energy spectrum that further depends on the location inside the solar system, e. g. Earth orbits or interplanetary space.

For material qualification and material engineering, individual irradiation is considered and their effects are superimposed. However, effects occurring when two and more radiation types simultaneously are present have barely been investigated yet. Further complexity is added, when additional interactions take place due to laboratory hardware.

Aims: This publication reports on the efforts made to analyse and measure the interaction of a VUV and corpuscular radiation sources. The aim is to quantify the deviations due to interactions and conclude consequences for the simultaneous operation of these radiation sources.

Methods: In order to quantify the effects, the Complex Irradiation Facility (CIF), located at the DLR Bremen has been used. It connects proton and electron accelerators together with VUV and UV light sources to an ultra high vacuum chamber. The corpuscular and VUV radiation sources have been operated simultaneously. The reaction of the operation parameters, such as current measured with Faraday Cups (FC) has been tracked and post-processed.

Results: It has been discovered, that protons considerably interact with the gas mixture used to operate the VUV source. This interaction decreases for higher beam intensities of the corpuscular irradiation. It was found, that this is likely due to protons ionizing gas atoms which are then measured by the FC as current. For electrons, this phenomena was not observed due to their smaller stopping power. The discovery restricts the acceleration factor of the CIF for proton together with VUV irradiation, but does not necessarily limit the range of application of the CIF depending on the requirements of the material and/or qualification test. Energy range of electrons stays unrestricted.

Keywords: vacuum ultra violet radiation, electrons, protons, qualification testing, material engineering

1. Introduction

The interplanetary space environment is composed of electromagnetic and corpuscular radiation originating from the Sun and from outside of the solar system. Particle radiation can be further subdivided into electrons, protons, alpha particles and further heavier ions. Each of these combinations of origin and radiation type are characterized by a spectrum of flux over particle or photon energy. For material design and qualifications testing, it is desirable to reproduce these spectra as accurate as possible. But, under terrestrial laboratory conditions, it is difficult to replicate a certain spectrum of a given particle species. This is also due to the reason, that accelerators are only capable of generating mono-energetic particles. Additionally, simultaneous operation of two or more particle sources can cause interaction of these and possibly influence radiation test outcomes. Furthermore, it is important to differentiate between interactions that also occur in space and those due to the laboratory setup.

At the German Aerospace Center (DLR) in Bremen, the Complex Irradiation Facility (CIF) is operated. It is an ultra-high vacuum system equipped with electron and proton accelerators, both with particle energies from 2.5 up to 100 keV, for sample irradiation. Additionally, light sources for the Vacuum Ultra Violet (VUV), ultra-violet (UV), visible and infrared range are available [1]. See figure 1 for a sketch of the setup. Thus, important properties of the space environment can be reproduced.

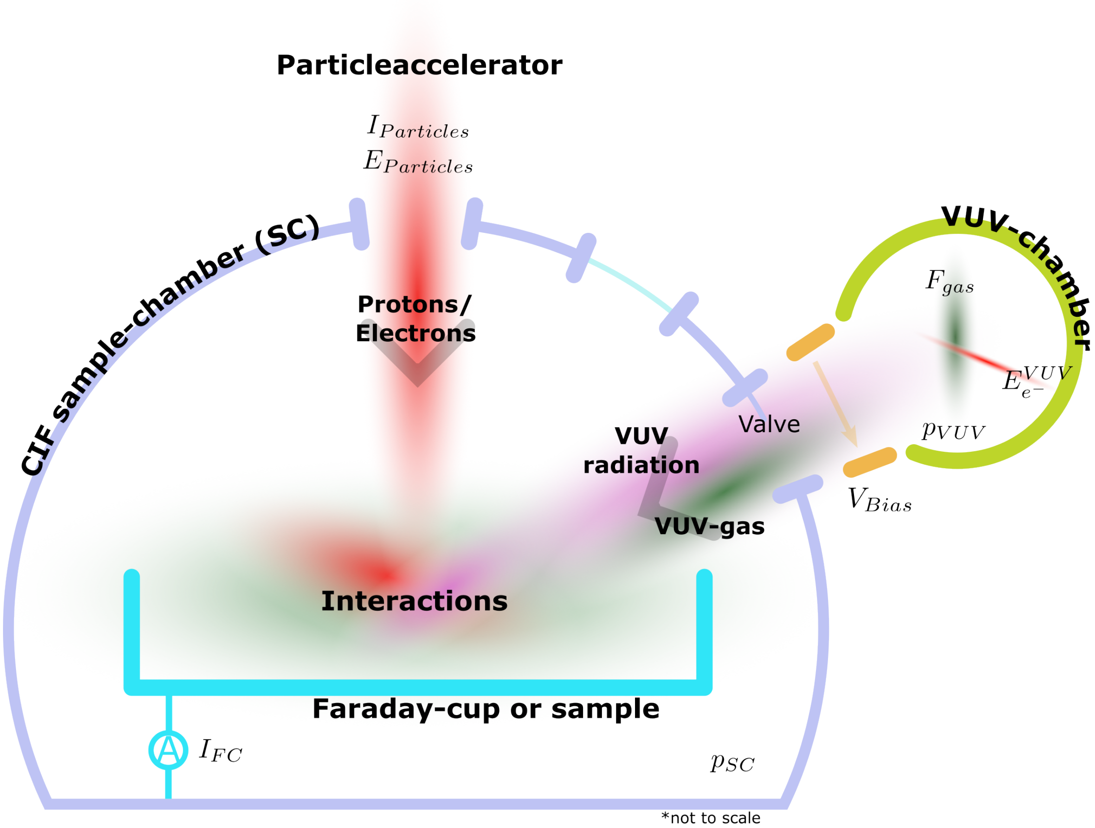

Figure 1. Sketch of the working principle of the CIF. Next to particle source and sample chamber, essential process parameters, such as current $I_{Particles}$ and energy $E_{Particles}$ of the charged particle beams, are displayed. Depiction not to scale.

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The VUV-light source employs a gas mixture (98% argon, 1.5% krypton, 0.5% helium) irradiated with electrons to produce a calibrated light spectrum from 40 nm to 410 nm [2]. The energetic electrons for the gas irradiation are produced by a dedicated particle accelerator inside of the VUV source. The majority of the argon gas used is pumped out of the system, but a non-negligible amount enters the sample chamber, where it interacts with the materials under test, but also with incoming particles from other radiation sources. Thus, the availability of VUV radiation comes at the cost of having to deal with interactions between these traces of gas and other radiation types used in the experiment.

The following content will initially describe the employed methods and explain the procedure and post-processing to obtain the data. After that, the results will be presented and discussed. Possible explanations for seen phenomena will be elaborated. Eventually a conclusion summarizes the presented results and suggests approaches to further investigate this matter.

2. Methods

In order to quantify the influence of the VUV radiation and the gas mixture on the particle beam, both have to be operated together and key parameters have to be measured. Key parameter, that can be observed, is the current I_{FC} measured at the centre Faraday cup (FC), see figure 1. It is assumed to be composed by following parts:

$$I_{FC} = \underbrace{I_{Particles}}_{\substack{\text{Protons/electrons}\\ \text{from accelerator}}} + \underbrace{I_{VUV}(E_{e^-}^{VUV}, F_{gas})}_{\substack{\text{VUV source}\\ \text{Photoelectric effect}\\ \text{Ions/electrons}\\ \text{from VUV chamber}}} + \underbrace{I_{Interaction}(I_{VUV}, I_{Particles}, E_{Particles})}_{\substack{\text{Ionized atom}\\ \text{secondary electrons}\\ \text{caused by interactions}}}, \quad (1)$$

where $I_{Particles}$ is the preset proton or electron beam intensity measured at the FC without VUV interaction. I_{VUV} depends on F_{gas} and $E_{e^-}^{VUV}$, gas inflow and energy of the electrons respectively, which describe process parameters of the VUV source, but have been kept constant throughout the experiments.

I_{VUV} was beforehand determined to be -1.38 ± 0.71 nA. This was conducted by irradiating the FC in the centre of the sample station, see figure 1, only by the VUV source repeatedly throughout the experiment.

Thus, I_{VUV} and $I_{Particles}$ each are the measured current when the FC is irradiated solely by either VUV or energetic particles, respectively.

$I_{Interaction}$ is here the remaining unknown quantity. The interaction current is dependent on I_{VUV}, $I_{Particles}$ and $E_{Particles}$ since these three variable describe quantitiy and properties of the interactions partners. To gain knowledge on dependencies, energy and current of the energetic particles have been swept over the range from 2.5 to 100 keV and a few nA up to 100 μA, respectively. As already mentioned, I_{VUV} has been kept constant.

For each combination of energy and current the procedure has been kept simple and was as following:

(i) The valve between Sample Chamber (SC) and VUV chamber is closed.

(ii) Particle source with either protons or electrons is running. Current $I_{Particles}$ can drift. See the dashed lines in figure 2.

(iii) VUV is running. Gas inflow is set to 1200 Standard Cubic Centimeters per Minute (sccm). Electron energy of the e-gun is set to 1 keV. This is the default operation mode of the VUV source. See reference [2]. For this mode, the emitted spectra is available.

(iv) Pressure inside the SC is below 10^{-6} mbar.

(v) I_{FC}, prior to opening of the valve, is tracked. It is later on used to estimate I_0.
(vi) The valve between VUV chamber and SC is opened.
(vii) The response of the current is tracked.
(viii) The valve is closed again.
(ix) New energy and/or current are set for the next iteration/test.

Figure 2 shows two exemplary plots of FC current and SC pressure. The plots refer to key points (v) to (vii). The valve opens for $t = 0\,s$. It can be immediately seen, that the pressure rises, possibly by several magnitudes, to values close to $2 \cdot 10^{-6}$ mbar, which is the operating pressure of the VUV source.

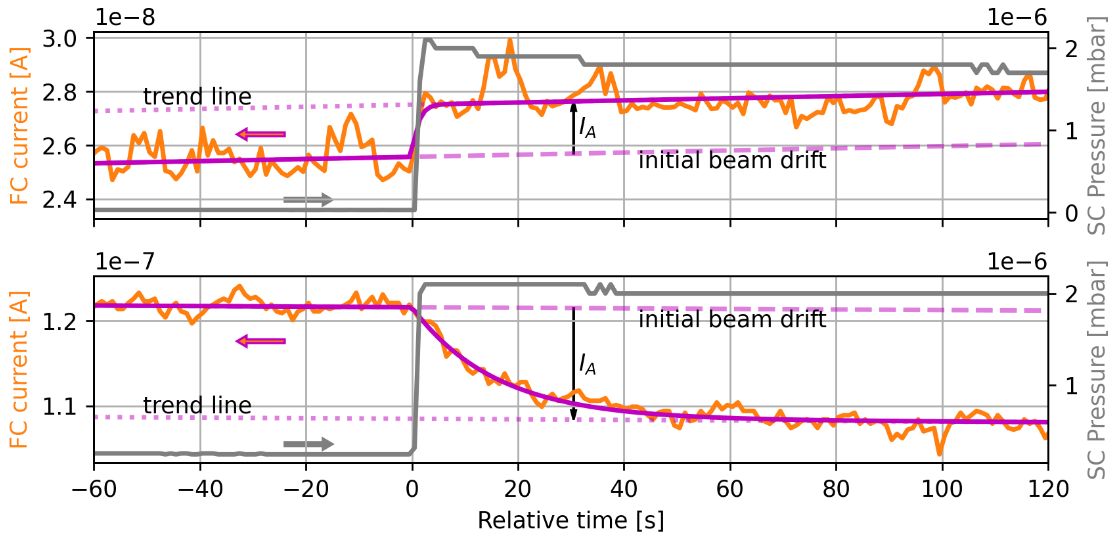

Figure 2. Exemplary plots to show the general sequence conducted for each test. Plots show test #26 and #34. Both show protons interacting with the VUV source. The dashed line depicts drift of the initial beam drift (equation 2: $d_I\,t + I_0$), the dotted line is the trend line, to which the new current tends (equation 2: $d_I\,t + I_0 + I_A$). It can be seen, that apart from similar initial states, the current decreases for one and increases for the other. Possible reasons for this will be discussed in section 3.

2.1. Post-Processing

During post-processing, the initial drift of the FC current has been estimated by a linear regression. See the dashed lines in figure 2 and equation 2.

$$I(t) = \begin{cases} d_I\,t + I_0, & \text{if } t \leq 0s \\ d_I\,t + I_0 + I_A[1 - \exp(-t/t_H)], & \text{otherwise} \end{cases} \tag{2}$$

After fitting the initial drift d_I and the current $I(t = 0s) = I_0$, the current change can be found via an least-square fit. I_A denotes the total current change or rather the vertical distance between initial drift and the trend line, t_H denotes the speed of change. The relative current change is than defined by $\Delta I = I_A/|I_0|$. $I(t)$ is plotted for two runs in figure 2. Since $I_{VUV} \ll I_{Particles}$, it is assumed that $I_A \approx I_{Interactions}$ and $I_0 \approx I_{Particles}$. ΔI therefore gives a good estimate of the influence of the interactions.

2.2. Faraday *cup bias voltage*

FCs in the CIF can be operated with bias voltage, in order to prevent secondary electrons from escaping and thus causing false current. It is stated, that up to energies of 160 MeV, a FC can be operated without bias voltage with sufficient efficiency [3, 4]. The shape of the FC, being an elongated cylinder, closed at one end, further hinders electrons from escaping. Therefore, and in order not to influence the interactions between gas, photons and charged particles, the FC was operated without bias voltage.

3. Results & Discussion

The procedure described in section 2 has been conducted for varies energies and currents. The number is broken down in figure 3. For protons, apparently, little changes in the initial conditions could have a big influence on the final result of a test run. Due to this unrepeatable behaviour of the protons interaction with the VUV source, the number of runs with protons was higher to gather further data.

Electrons behaviour is overall predictable. ΔI fluctuated little from run to run. See figure 4.

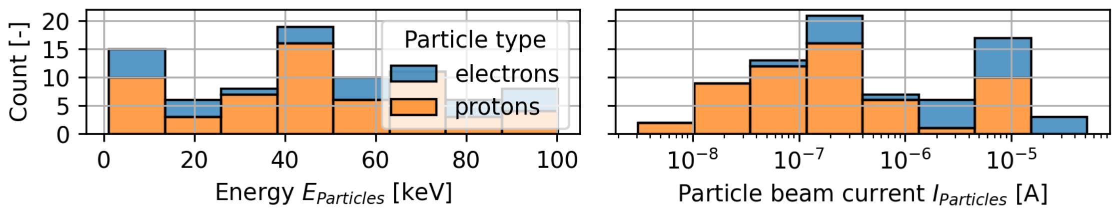

Figure 3. Stacked histograms of the tests conducted. Shown are the number of experiments for various energies and currents. Height of histogram gives number of runs conducted in given energy or current bin. A total of 83 runs have been performed.

The current on the central FC, when irradiated solely by the VUV source, was measured to be of a few nA, see above. It is unclear whether the measured current is caused by ions, electrons or due to the photoelectric effect. The current increases slightly with age of the e-gun cathode.

Furthermore, an angle dependency was investigated. As seen in figure 1 the FC is irradiated at an angle of 60°, turning the FC towards the VUV source causes an increase in current up to ∼30 nA when the FC is pointed towards the VUV source.

Figure 4 shows the relative current change ΔI of the particle beam after opening of the valve, which is I_A divided by absolute of initial beam current I_0. It is immediately seen, that protons interact differently with the VUV source, than the electrons.

The data is further sampled into dependencies on particle energies $E_{Particle}$ and initial currents I_0 in figure 5. Next to it, the total current change is plotted. Here, positive values indicate increase in positive charges measured at the FC and vice versa for negative values. There is no correlation between particle energy and current change, especially *total* current change. The relative current change decreases with increasing initial current, however the total change increases.

What is further remarkable, is that the adaptation time, see t_h in equation 2 varied widely, from only sub-seconds to several seconds, indicating a dynamic process. Further, t_h appears to correlate with the absolute current change $|I_A|$ (correlation factor of 0.4), indicating that a

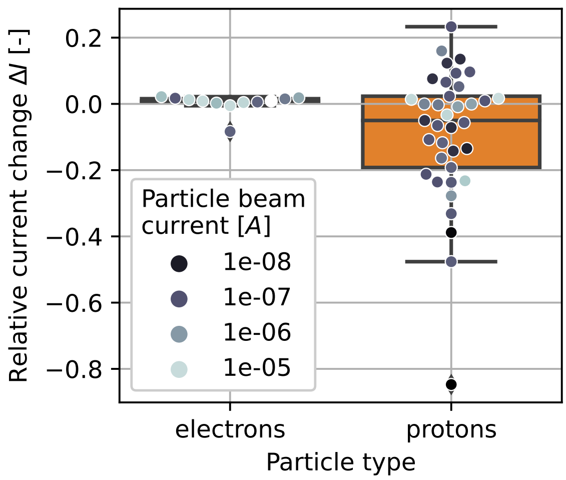

Figure 4. The figure show the distribution of the relative current change ΔI for all conducted runs divided by particle type, see figure 3. Protons reaction on the interaction with the gas and the VUV radiation is far more diverse, than that of the electrons. The measured current can halve itself or increase by 20 %. The brighter the dot, the higher the particle beam current. It can be seen, for protons, that higher currents are gathered in the centre of the distribution, but not entirely. On average, the measured FC current changed by -8.3±31.9% after interaction of the VUV source with protons and +0.5±3.5% with electrons. A further differentiation shall be done below.

charge is build up in the gas and than discharging at the FC.

Mainly relevant for the creation of charge in a penetrated medium is the stopping power of protons and electrons in argon gas for this application. Ionized atoms and their counterpart, the secondary electrons, inside the gas can than strike the FC and be there perceived as charge, just like the accelerated protons or electrons.

In figure 6 the stopping power for protons and electrons in argon gas is plotted [5]. The reader can see, that for any energy inside the investigated range, the stopping power of protons is bigger, than that of electrons. Protons are more likely to ionize atoms than electrons along their path through matter [6]. This can be attributed to the electrons property, to only after reaching energies of 10 MeV and higher, to interact with the shell electrons of the absorber [7]. Below this threshold, the interaction takes place with the Coulomb field of the nucleus without ionization. Furthermore, the penetration depth of protons is, due to the higher stopping power, by magnitudes smaller than that of electrons [5].

From this it can be concluded, that the current change of electrons is likely attributed to shadowing due to the entering gas from the VUV source. Therefore, the perceived negative charges by the FC decreases and fluctuates only little due to few ionizations taking place.

For protons it is different. Due to their higher stopping power and therefore higher energy transfer to the penetrated matter, they create a plasma along their trajectory. These charges, either ions or secondary electrons, are than measured by the FC. Due to the plasma dynamics, the perceived charge on the FC can vary widely, and even de- and increase the measured current. Conceivably as seen in figure 4 and 5. This process is independent of the particle energy, due to the stopping power, describing the energy transfer, being sufficiently high enough to ionize molecules in any run.

Figure 7 summarizes this behaviour for electrons and protons. The initial current has been binned to emphasize the dependence of the current change on the beam intensity. For electrons, the influence is negligible for all beam currents. For protons, the deviation decreases with increasing beam intensity. For protons currents, of approximately 1 μA and higher, tests with protons in combination with the VUV source can be conducted.

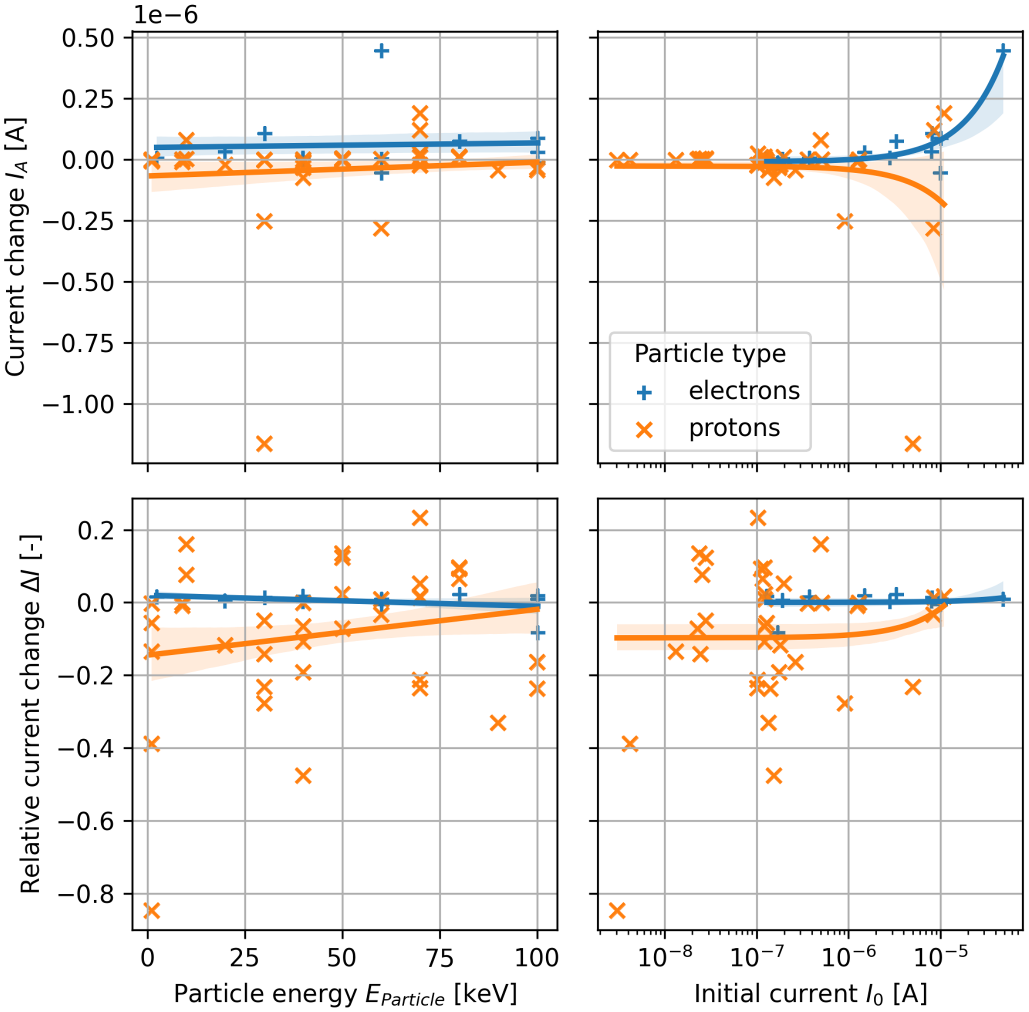

Figure 5. Initial current I_0 and energy $E_{Particle}$ plotted over relative and absolute current change, ΔI and I_A respectively. Furthermore, a regression line is plotted, accompanied by a confidence interval of 68% denoting the standard deviation. No correlation between energy and current change can be detected. For higher initial currents I_0 the relative change disappears, however the total change increases.

Looking at this phenomenon from the point of view of material qualification, the created charges can alter the outcome depending on the composition of the material under investigation. Even though, the created plasma contains ions and free electrons with small kinetic energies and charges [8], it can ionize further atoms and thus alter the analysis and outcome. For higher currents, the influence disappears compared to the actual effect of proton irradiation.

In figure 8 the acceleration factors of the CIF for a Low Earth Orbit (LEO), Geostationary Orbit (GEO) and interplanetary mission at one Astronomical Unit (AU) distance are plotted. The acceleration factor is defined by the ratio between possible flux in laboratory and that in the space environment. Since the flux in the CIF is adjustable in a certain range (See figures 3

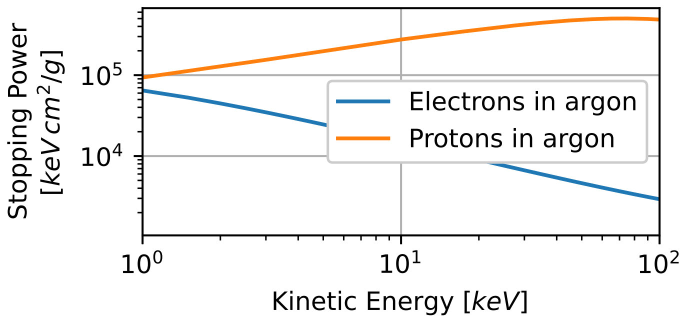

Figure 6. Comparison of stopping powers for electrons and protons in argon, denoting the gas mixture, calculated from [5]. For any energy employed in the CIF, the stopping power of protons is higher than that of electrons. This can vary for different materials.

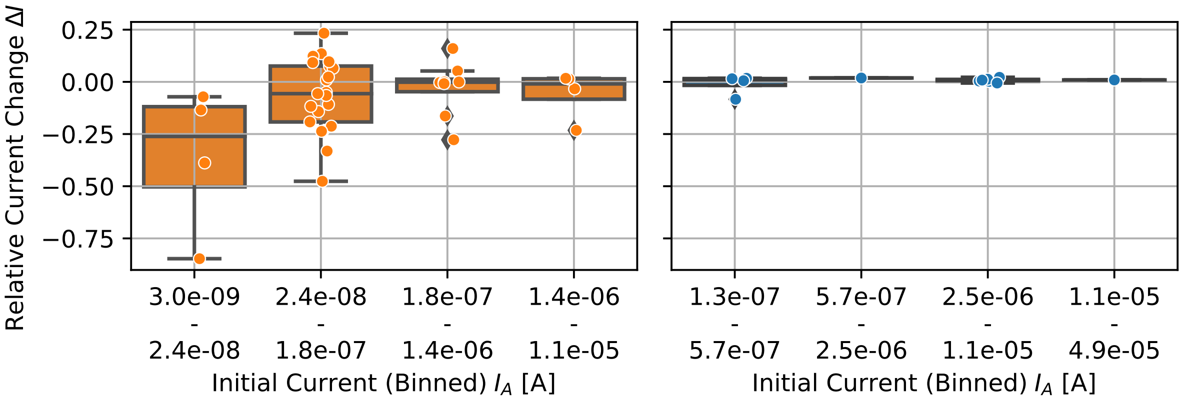

Figure 7. Box plots for binned initial current. The plot shows change in fluctuation for increasing beam intensities compared to figure 4. For protons, it is remarkable, that for increasing intensity the deviation from the original current not only decreases, but also the fluctuation decreases. As already mentioned, electrons act over all stable.

and 7), the acceleration factor also can vary inside limitations. The restricted current range of the proton source, when operated with the VUV source is located at the top of the full range.

Whether or not the restriction of the proton source can affect quality of the radiation testing depends strongly on environment and material selection. It has been shown, that e. g. aluminium oxide tends to form hydrogen blisters at higher fluxes [12, 13], which has to be weighted into the planning for material testing. This does not necessarily restrict the testing options, since the acceleration factor also depends on the environment. And whether or not a high acceleration factor can influence the test outcome depends further on the material.

Eventually it is noteworthy to mention, that it is uncertain what role the geometry of the FC, being a cylinder, plays and needs further investigation. Gas originating from the VUV source can be blown into FC body, could conceivably get caught there and be increasingly exposed to the particle irradiation. Comparing measurements with a simpler FC, consisting of a plate, will likely solve this open question.

4. Conclusion

This publication investigated the interaction between charged particles and the VUV source of the CIF at the DLR Bremen. It was observed, that the gas, used to produce the electromagnetic

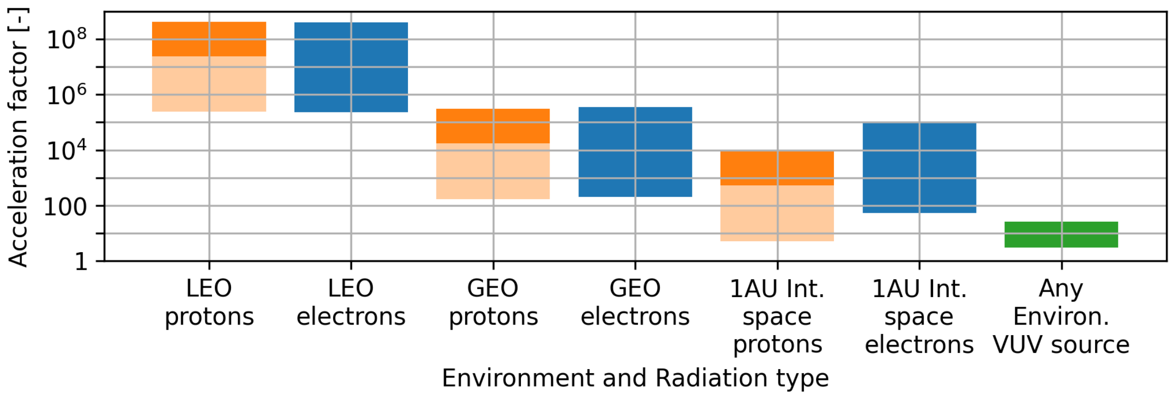

Figure 8. Exemplary acceleration factors for the proton, electron and VUV source inside the CIF for LEO, GEO and interplanetary space at 1 AU. Fluxes considered are taken from [9–11] in the range of 1 to 100 keV. Light orange denotes the full range, while the dark orange marks the restricted (1 μA and higher) share of that range when testing in combination with the VUV source. Electrons and VUV are unrestricted. The particles are swept over an area of 6 by 6 cm^2. The current varies in the range shown in figure 7. The acceleration factor of the VUV source ranges from 3 to 26.3 [2], which is valid anywhere outside the Earth atmosphere at a distance of 1 AU to the sun.

light, has significant influence on the current measured. It was found that, while for electrons the interaction is restricted to shadowing due to the gas, protons show different mechanisms as their ionization rate exceeds that of electrons. The created charges are than perceived as either positive or negative by the measuring FC. Figure 7 shows the relative current change ΔI for bins of initial current I_0 to differentiate further between low and high beam intensities. As already indicated in figure 5, for high initial beam currents, the deviation vanishes. For a minimal relative deviation from the initial current it is recommended to use currents of 1 μA and higher. For electrons, there is no restriction.

Nonetheless, it is necessary to firstly further investigate this effect, by follow on experiments and simulations. Secondly to implement the gained knowledge into the calculation of uncertainties for total fluence. And thirdly to improve the setup of the VUV source, for instance by adding another turbo molecular pump to either the VUV or sample chamber.

Follow on experiments should include other shapes of FCs, as the geometry, a cylinder, possibly traps gas and eases the plasma production by incident charged protons. A possible geometry can be a simple plate. Escaping secondary electrons will than have to be considered. Mass spectrometer measurements shall be further investigated as well. Furthermore, the gas temperature is of high interest in order to estimate the number density.

For simulation, either Geometry and Tracking (GEANT4) or Spacecraft Plasma Interaction System (SPIS) are being considered.

Conflict of Interest Statement

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Author Contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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Data Availability Statement

For original data, inquiries can be directed to the corresponding author.

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