General Studies Programm (GSP) Activity

Laser-Plasma-Accelerator's Potential to Radically Transform Space Radiation Testing

by

University of Strathclyde

Universität Hamburg
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2013

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ESA General Studies Programme (GSP) Activity

Contract No. GSP-SOW-10-xx116 // RFQ 3-13258/11/NL/AF

Final Report

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Hamburg, Germany

2013

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1 Executive Summary

Laser-plasma-accelerators are relatively new accelerator devices which are characterized by being very compact, which is the result of the giant electric accelerating fields present in strongly focused, high-power ultrashort laser pulses. Peak intensities of modern laser systems can reach 10^{22} W/cm^2 or more, which is many orders of magnitude larger than the complete sunlight incident on Earth, if it were collected and focused at the same time onto an area of a tip of a pencil. Such intensities make such laser systems attractive for many applications, as exotic as inertial confinement fusion and producing ultrashort electron beams with GeV-scale energies or advanced light sources such as free-electron lasers, or those based on inverse Compton scattering and betatron radiation. The woldwide booming community in this fields works towards these applications which have highly stringent demands on beam quality, as an alternative to well-established accelerators based on radiofrequency cavity based accelerators such as linacs (for electrons) and cyclotrons (for protons and ions). Breakthroughs were achieved in 2004, when for the first time instead of spectrally very broadband and rather divergent particle beams, pencil-like electron beams with quasi-monoenergetic electron bunch distribution were generated. Beam quality in terms of narrow energy spread and larger energies (beyond the GeV barrier) improves continuously and rapidly, fueled by progress in terms of understanding and by ever increasing laser power and technology readiness. In contrast to such highest-quality beams which are needed for example for free-electron-lasers, space radiation which harms electronics and living systems outside Earth's protective magnetic fields, is always very broadband. In fact, conventional accelerators always automatically produce very narrowband particle beams, which are unnatural. It has been proposed (and patented) for the first time in 2009 to use compact laser-plasma-accelerators to produce broadband radiation such as present in space and to use this for radiation hardness tests. Such broadband radiation is the inherent regime of laser-plasma-accelerators. The difficulty of laser-plasma-accelerators to produce monoenergetic beams is turned into a noted advantage here. Since producing broadband radiation is possible since many years with laser-plasma-accelerators, this application is one which has been "left behind" for many years now due to the community seeking to produce more monoenergetic beams such as with conventional accelerators.

Recent proof-of-concept experiments in a project which merged state-of-the-art space radiation testing with state-of-the-art laser-plasma acceleration has shown that by using laser-plasma-accelerators it is possible to reproduce the spectral characteristics of radiation belt "killer electrons" for example, which populate the radiation belts on GEO orbits, for instance. This especially prominent type of space radiation was for the first time produced in the laboratory here on Earth in a well-controlled manner and seems to be a a natural candi-

date as a benchmark for other radiation sources, which produce monoenergetic beams based on which also the use of degraders cannot reproduce space radiation which is characterized by a decreasing (often exponentially decreasing) spectral flux towards higher particle energies. Spectral flux shaping by tuning the laser-plasma-interaction parameters has been demonstrated, for example to reproduce the electron flux incident on satellites on GPS orbits according to the AE8 model. Sophisticated diagnostics, readily available from the laser-plasma-community as well as the traditional accelerator community, which are increasingly merging (again), have been used to characterize and monitor the flux. State-of-the-art radiation hardness testing techniques have been adapted to the laser-plasma radiation source environment, test devices have been exposed to laser-plasma-generated space radiation and it was shown that the performance of these electronic devices was degraded. With the exception of doing radiation tests directly in space, these irradiation campaigns may have been the most realistic space radiation tests to be carried out in the laboratory here on Earth to date. The approach of reproducing space radiation flux directly in the lab has hitherto not been accessible, which is why approximative techniques employing monoenergetic beams had to be used. This clearly demonstrated the applicability of laser-plasma-accelerators for space radiation reproduction, and is currently triggering large interest in the laser-plasma-community. Other advantages of laser-plasma-accelerators are that they can produce electrons, protons and ions alike – even at the same time – as well as enormous peak flux, which may allow for exploration of nonlinear response of electronics and biological systems.

Both fields, laser-plasma-acceleration on the one hand and space radiation testing on the other are highly vibrant fields, which have been disjunct so far. Connecting both fields, and to introduce laser-plasma-accelerators as complementary radiation sources for improved space radiation testing is highly advisable. It shall be emphasized that both the traditional radiation sources as well as laser-plasma-accelerators have inherent advantages, and that it is expected that the combination of both types of radiation sources will be highly fruitful for the further development of the space radiation field. Obvious strenghts of laser-plasma-accelerators are the production of broadband particle flux, and the enormous flexibility, compactness and tunability. For example, the devlopment of a test standard for radiation belt electron radiation effects with laser-plasma-accelerators seems advisable, which could then serve as a benchmark for other radiation sources. On the other hand, it is much harder to produce higher energy protons and ions with laser-plasma-accelerators than electrons. This said, the progress in the laser-plasma-accelerator tecnology is rapid, and protons and ions with several hundreds of MeV have already been produced. The highest proton and ion energies are always reached with large, cutting edge laser facilities, but it has been learned from the last years that steady and ongoing advances

in laser technology quickly converts prototype, cutting edge laser technology to commercially available off-the-shelf products. Highest power (hundreds of TW or even PW) laser systems are also characterized by relatively low repetition rate (typically, 10 Hz or less), but there is much movement on this front, too, and kHz systems are already available. Generally speaking, the higher the obtainable particle energies, the lower the repetition rate. This further supports the advised strategy to start the establishment of laser-plasma-accelerators in the space radiation field with reproduction of broadband, lower energy electrons and protons. In this regime, the laser shot repetition rate can be very high, currently up to hundreds of kHz, which increases the average flux. It is estimated that with such systems, for example satellite-relevant fluence can be produced within irradiation times which are orders of magnitude shorter than at large facilities. The development of high power thin-disk and fiber lasers and optical parametric amplification (OPA) technology deserves special attention. Such lasers do not only allow for highest repetition rates, but also for an especially compact setup, best cost-effectiveness and a very high wall-plug power efficiency. Such compact devices with ever increasing powers, repetition rates and therefore obtainable radiation flux levels may end up in the future as compact radiation sources without proliferation issues available on site at chip and electronic manufacturers, and in the air- and spacecraft community.

Further increased communication between the laser-plasma-accelerator community and the space radiation community is highly desirable. This should contain further collaborative R&D acitivities, as well as networking, ideally on a European level. Such a network could bundle the needs and requirements for the most efficient use of laser-plasma-accelerators, for example to ameliorate the shortness of available beamtime for radiation tests which the space radiation community faces today. Based on such a network, a coordinated strategy should be developed which ideally would integrate the European space entities, as well as the traditional accelerator and the laser-plasma-accelerator community. For example, the establishment of laser-plasma-accelerator systems at space radiation testing clusters, for example at ESTEC, and in turn the formation of a dedicated space radiation testing beamline at application-oriented laser-plasma-facilities such as the Scottish Centre for the Application of Plasma-based Accelerators (SCAPA) or at facilities of the European Extreme Light Infrastructure (ELI) seems promising. Even mobile laser-plasma-accelerator devices, mounted on mobile trucks, may be feasible. At the same time, the use of plasma afterburner stages which may convert monoenergetic in broadband flux should be considered.

2 Introduction

Radiation in space is one of the major threats to manned and unmanned missions. With an ever increasing number and complexity of space missions, and at the same time increasing demands on the performance of electronics onboard space vessels, this fundamental problem is continuing to grow more and more important. European Space Agency and space entities all over the world are constantly developing and using various strategies and countermeasures in order to respond to this threat. For testing of electronics one would generally want to reproduce the actual spectral environment in space as accurately as possible in order to get the most meaningful test results. Furthermore one wants to have radiation facilities which are easily accessible. However, state-of-the-art accelerators are based on radiofrequency cavity acceleration and cyclotrons, where the accelerating fields are limited to electric fields of the order of tens of MeV. This results in acceleration distances of tens of meters or more, and thus requires large devices. These facilities are therefore stationary and limited in number due to rather large maintenance costs. Meanwhile, the demand for accessible beamtime is rising.

Laser-plasma-accelerators can be very compact, "table-top" devices because the electric fields are as high as tens or even hundreds of gigavolts-per-meter. This is three or four orders of magnitude higher than with conventional accelerators, so that in turn comparable particle energies can be reached in mm oder cm-scale distances. In the broadest sense, the concept of collective, plasma-based acceleration was originally proposed at a conference of the accelerator community at CERN [2–4]. However, means to purposefully manipulate plasma in order to achieve the desired acceleration were not available at that time. The development of the laser, and the chirped pulse amplification technique in 1985 [5] were important milestones which allowed to generate laser pulses with focused intensities where not only gases or other targets such as droplets or solids are almost immediately ionized by the ultrahigh electric fields, but also the resulting plasma electrons are rapidly moving in the oscillating laser field. This leads to various process by which electrons can be accelerated in various directions. While protons and ions cannot be accelerated directly in today's available laser intensities due their larger mass (but they will be with next-generation lasers!), they are efficiently accelerated as a secondary effect: the plasma electrons, being accelerated in various preferential directions by the laser pulse, produce quasi-stationary fields which on the timescale of the plasma protons and ions live long enough to accelerate the protons and ions to high energies.

The acceleration of electrons and protons with laser-plasma-accelerators really started in the 1990s, when high-power laser technology was more and more introduced in large research centers for fundamental science. It quickly became

clear that laser-plasma-accelerators are indeed an effective means to accelerate electrons [6] and protons, but this remained initially disjunct from the mainstream accelerator field. Laser-plasma-acceleration then took off on its triumphal course, and now can look back to various milestones in the last decade. One of these was the generation of quasi-monoenergetic electrons in 2004, achieved at three research centres in the UK, US and France [7–10]. This breakthrough made it to the cover of *Nature* with the headline "Dream Beams". Another was the first generation of non-thermal protons in 2006 [**?**, 11, 12]. Today, main research directions are light sources [13, 14], which need highest quality electron beams to convert the electron beam into photon pulses such as in a free-electron-laser, another is the generation of protons and ions and the study of warm dense matter and fusion. Many other applications exist, for which even intensities beyond $10^{25}\,\mathrm{W/cm^2}$ are needed and where particle physics can be explored, such as quantum effects as exotic as breaking Schwinger limit [15].

The quest for ever higher laser powers and intensities is reflected by networks such as the International Committee on Ultra-High Intensity Lasers ICUIL. The ICUIL worl map of ultrahigh intensity lasers is depicted in figure 1. What is especially remarkable about this in the context of the present report are two things: first, that measured by the laser intensity and power levels of the systems of the map today, this map would have been practically empty just a few years ago. This shows vividly how rapid the progress in laser system capabilities is. Second, it indicates that Europe is leading the field as regards the number

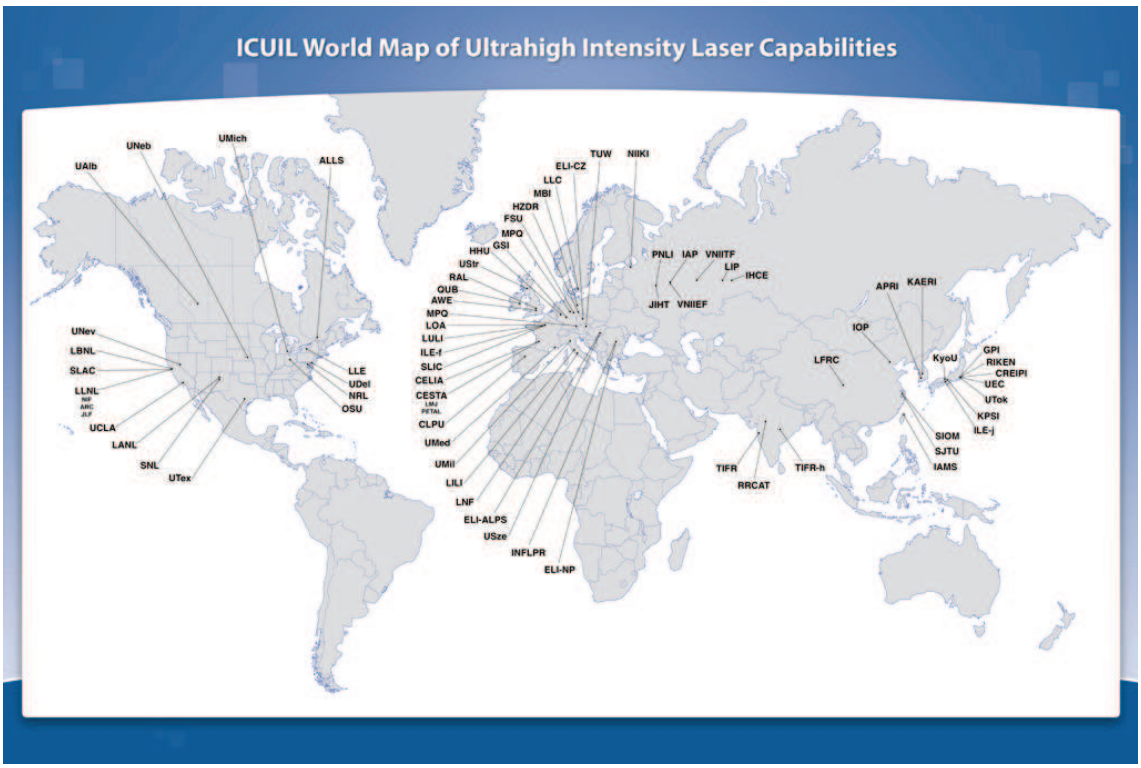

Figure 1: ICUIL world map of ultrahigh intensity laser systems.

of facilities. What is not seen on the map is that there are a huge number of laser systems which are mostly smaller than the laser systems on the map, but are well capable to accelerate particles via laser-plasma-acceleration. More and more laser systems are commissioned practically every week. This is also due to the fact that even PW-class laser systems for particle acceleration are today commercially available.

Many applications pursued by the laser-plasma-community demand for the highest electron beam quality (such as for Free-Electron Lasers [13, 14]) or proton beam quality (such as for proton cancer therapy [16–18]) in terms of divergence and monochromacity. The application of using laser-produced particles for the reproduction of space radiation and to test the radiation hardness of electronics [1, 19–21], in contrast, can work with broadband and strongly divergent electron and proton beams. This is a dramatic advantage, because the production of broadband and divergent beams is the inherent regime of laser-plasma-accelerators. In fact, it is much harder to produce monoenergetic beams with laser-plasma-accelerators than broadband ones. Moreover, the radiation in space is also not monoenergetic, but broadband! It is therefore in principle an obvious idea to introduce laser-plasma-accelerators to the field of space radiation reproduction and electronics testing. This was proposed in 2010/2011 [21], and in the context of the present study, design considerations for this application have been published in 2012 [1], and proof-of-concept experiments have been carried through recently in the context of this and a related project [22], which will be summarized in the next section.

3 Proof-of-Concept experiments with laser-plasma-produced space radiation

The 150+ TW Ti:Sapphire laser system Arcturus [23] at the Institute for Laser and Plasma Physics at Heinrich-Heine-University Düsseldorf was used to irradiate thin aluminum target foils. Here, the laser pulse with an energy of $E \approx 1.2$ J in a duration of 23 fs is incident on the Al foil at intensities of the order of a few 10^{19} W/cm^2, generates a plasma and leads to the production of broadband electron and proton bunches into various emission directions. The whole process takes place in an evacuated target chamber and is depicted in figure 2.

The compressed laser pulse is incident from the right hand side and then is send to the 90° focusing parabola. The F/2 parabola then focuses the laser beam on the target foil, which was moved after each shot to provide a fresh surface for the interaction process. Before the laser pulse reaches the traget foil, no radiation is produced. An image plate (IP) stack, which also can hold the devices under test (DUT's), to record the electron flux in forward direction is put on axis. On

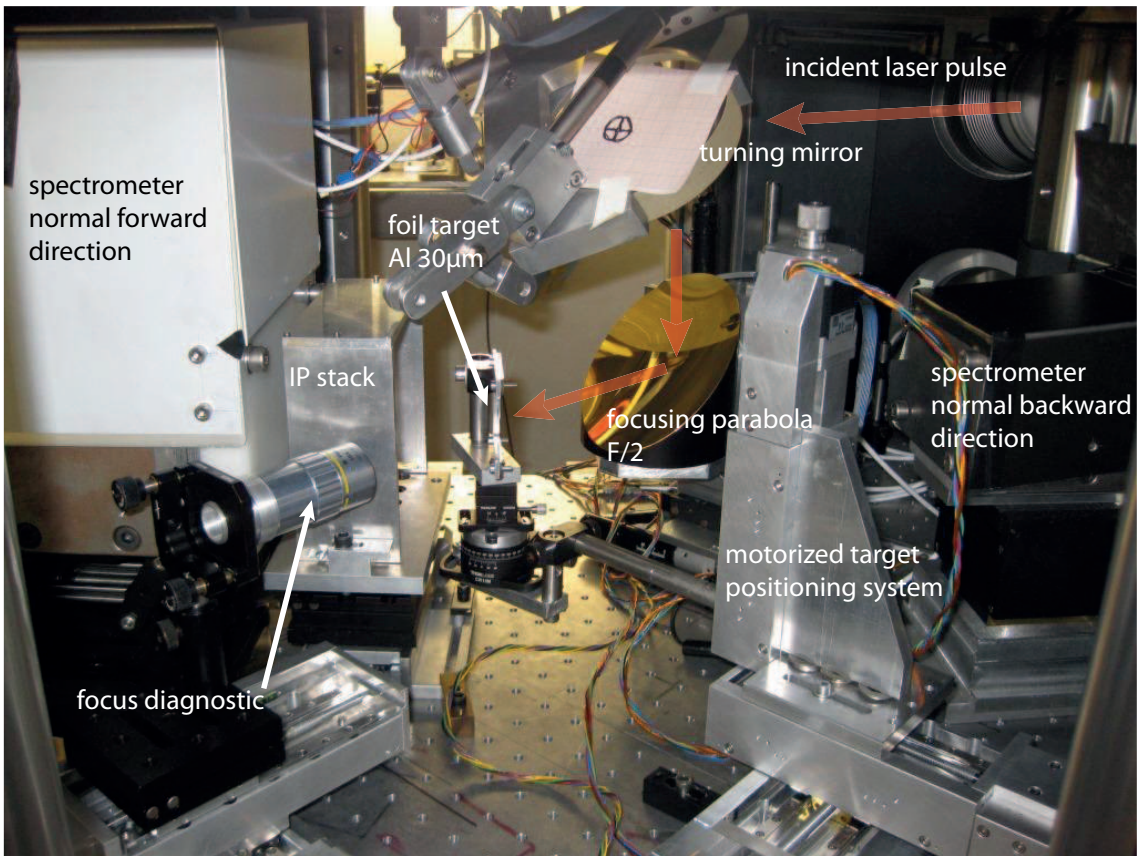

Figure 2: Setup inside the irradiation chamber. The indident laser system is strongly focused on an Aluminum foil target, where the radiation is produced. Focus diagnostic microscope objective, image plate (IP) stack and permanent magnet based spectrometers in forward and backward direction are shown next to the target foil positioning system.

axis, the stack has a central hole where electrons (and protons) could pass and enter a magnetic spectrometer for further energy measurement. The magnetic spectrometer is a more accurate and can be monitored online, while the IP stack has the advantage of covering a large area and thus large parts of the emitted flux.

In the experimental proof-of-concept campaigns of [22], it was focused on the production of so called 'killer' electrons in the van Allen belts [24–26]. In the radiation belts of Earth, these electrons have spectral flux which decreases following a power-law or exponential distribution, where the number of electrons N per MeV decreases according to

$$N \propto \exp\left(\frac{E_{\text{kin}}}{k_B T}\right) = \exp\left(\frac{E_{\text{kin}}}{T_{\text{eff}}}\right) \tag{1}$$

where k_B is Boltzmann's constant, T is the electron temperature in Kelvin, and $T_{\text{eff}} = k_B T$ is the so called effective electron temperature in eV.

Figure 3 shows explicitly for space radiation, that at certain fixed orbits, the radiation belt electron flux does also follow an exponential decrease. As an ex-

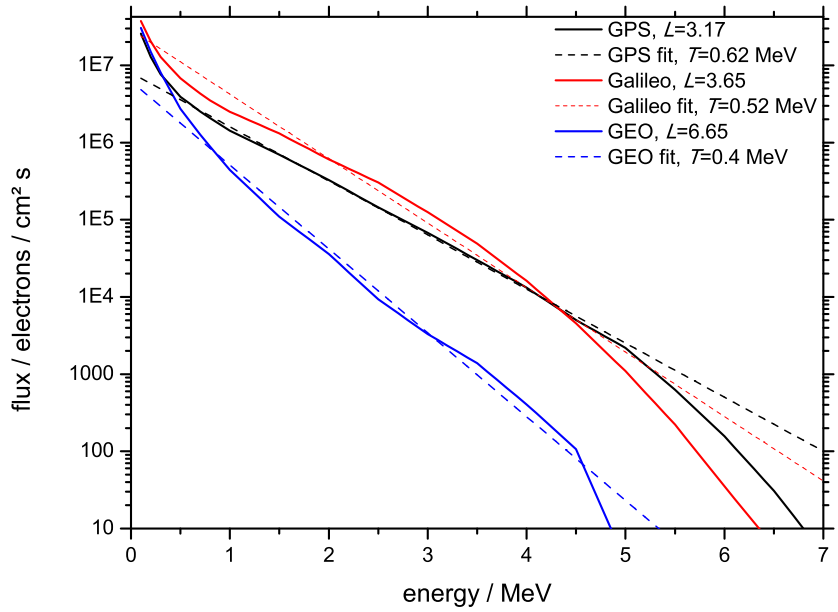

Figure 3: Electron flux according to $AE8_{max}$ at the important orbital distances of GPS, Galileo (both around medium Earth orbits (MEO)) and at geosynchronous orbit (GEO). Fitting exponential particle distributions leads to temperatures in the range of $T_{\text{eff}} \approx 0.4 - 0.62$ MeV (from [1]).

ample, the electron flux at $L = 3.17$ (GPS), $L = 3.65$ (Galileo), and $L = 6.65$ (GEO) are plotted based on NASA's van Allen belt $AE8_{max}$ model [27] for spectral flux during solar maximum activity. By fitting an exponential decay function, effective temperatures $T_{\text{eff}} \approx 0.4 - 0.62$ MeV can be deduced.

Reproduction of "killer" radiation belt electrons is an excellent showcase for laser-plasma-produced electron beams, since in the laser-plasma-community the concept of exponential spectral flux and effective temperatures is also well known. Engineering scaling laws have been developed which predict the electron temperature of electron beams generated during laser-solid interaction in dependence of the focused laser intensity. The scaling of Wilks [28] predicts

$$T_{\text{eff, Wilks}} = (\sqrt{1 + I[\text{W/cm}^2]\lambda[\bar{\text{m}}]^2/(1.37 \times 10^{18})} - 1)m_0c^2 \,. \tag{2}$$

while another scaling for slightly different laser-plasma-parameters was developed by Beg [29]. It differs from Wilks' scaling in that it predicts higher temperatures for intensities lower than $\approx 2.8 \times 10^{18}\,\text{W/cm}^2$ and lower temperatures than Wilks for higher intensities. Explicitly, it is

$$T_{\text{eff, Beg}} = 0.1(I_{17}\lambda^2)^{1/3}\,\text{MeV} \tag{3}$$

where I_{17} gives the intensity in multiples of $10^{17}\,\text{W/cm}^2$. A new analytical approach to the electron temperature scaling was made recently by Kluge et al. [30] which fits the experimental and numerical data in the range of $a_0 \approx 5$ as good as the Beg-scalings and for $a_0 < 1$ fits to the ponderomotive scaling of Wilks.

These steering laws and the sophisticated diagnostics, consisting of imaging plates, beam viewers and the like, were used to optimize the electron beam output and to approximate the spectral flux predicted by the $AE8_{max}$ model as good as possible. For example, figure 4 shows the spectral flux expected on GPS orbit at $L \approx 3.17$ (black solid line), an exponential fit (black dashed line) and optimized measured spectra in the target normal forward (red) and backward (green) direction. The left y-axis gives the electron flux per square centimeter, the right y-axis the electrons per MeV per msr. It is seen that there is an excellent agreement between the real flux in space and the lab radiation, especially in the important medium energy range. The lower energy range < 1 MeV is not exactly known since it is not very well measurable (this holds for both the situation in space as well as in the lab due to the spectrometer cutoff), neither is it particularly relevant (notable expection: surface charging) because low energies are more easily blocked. The mismatch in the higher electron energy range is also of secondary concern, because (note the logarithmic scaling) the number of electrons is much less here in any case.

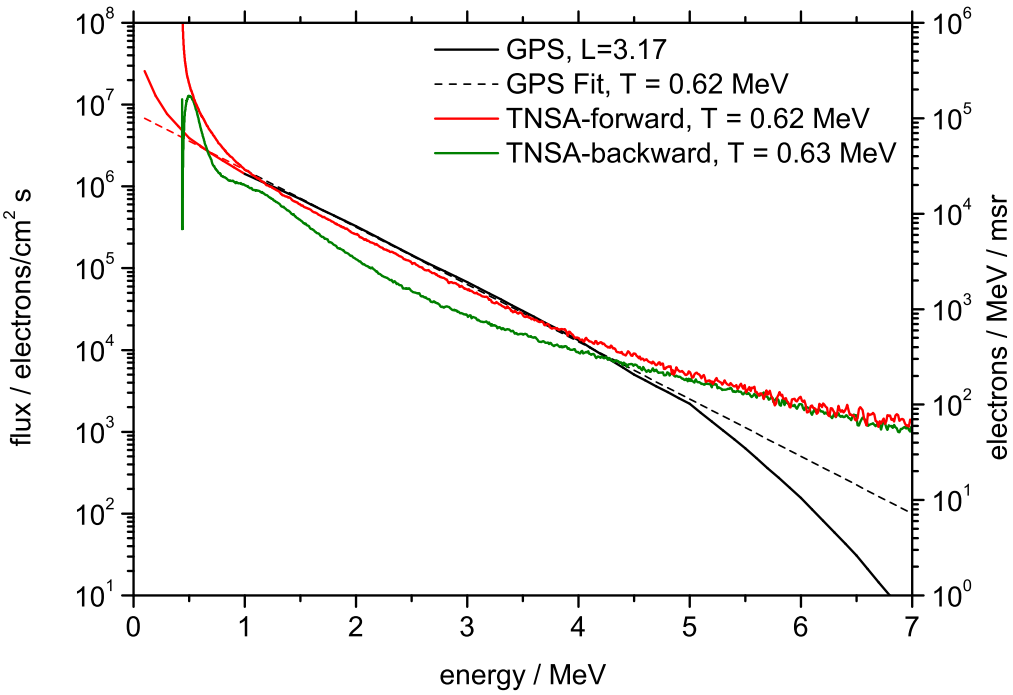

Figure 4: First laboratory based reproduction of space radiation (as present at GPS satellite level) with laser-plasma-generated bunches in the present project.)

Next, space-relevant electronic test devices were used to demonstrate and explore the radiation damage of such laboratory-produced space-radiation. Optocouplers were chosen because these are relatively compact devices for which radiation damage can be determined straightforwardly using the current transfer ratio. Figure 5 shows on the left hand side how various optocouplers have been mounted onto an anodized aluminum foil and were then put behind a proton filter layer and in front of a combination of an image plate sandwich stack

and a magnetic spectrometer. The right hand side of figure 5 shows the resulting radiography image on the electron sensitive image plates. The level of detail resolved by this diagnostics (e.g., one can see clearly the different pins and the inside of the spectrometer) indicates the accuracy of measurements.

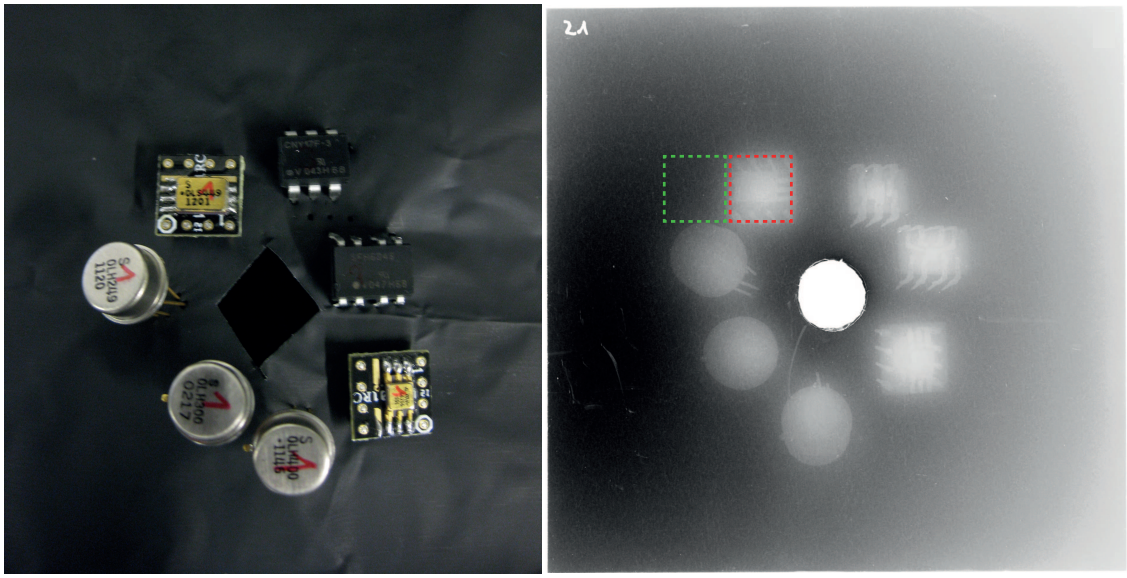

Figure 5: Left: Set of optocouplers on mounting foil. Right: Radiography image on image plate resulting from irradiation.

The optocouplers were tested before and after irradiation at ESTEC using state-of-the-art test procedures and devices. A clear irradiation damage is shown in figure 6 for the optocoupler model Vishay SFH6345, for which the current transfer ratio CTR was measured for input currents of $I_f = 100^{-}$A and $I_f = 1\,$mA, respectively, before and after irradiation. In figure 6, the CTR of not irradiated (but otherwise treated and stored in the same conditions as the other optocouplers) reference optocouplers (DUT's # 30-60) is displayed and encircled with a blue dashed oval. As is clearly seen, the CTR of the not irradiated optocouplers is unchanged. In this campaign, there was one group of optocouplers (tagged with "1" and "2" in figure 6, respectively) which was exposed to $3.2 \times 10^6\,\mathrm{e}^-/\mathrm{cm}^2$ in the target normal forward and backward direction, respectively, in one irradiation block and then in combination with a second irradiation block with in total $4.6 \times 10^7\,\mathrm{e}^-/\mathrm{cm}^2$. After exposure to $3.2 \times 10^6\,\mathrm{e}^-/\mathrm{cm}^2$ the optocouplers were again taken from Düsseldorf to Noordwijk to ESTEC, and the CTR was determined again. No significant degradation of CTR was observed. Even after the next irradiation block in Düsseldorf, when the fluence was increased to $4.6 \times 10^7\,\mathrm{e}^-/\mathrm{cm}^2$, hardly a degradation of CTR performance could be measured at ESTEC. In contrast, optocouplers from group 3 and 4, which were exposed to a far higher fluence, namely at maximum $2.1 \times 10^9\,\mathrm{e}^-/\mathrm{cm}^2$, show a significant (a thorough error anaylsis was performed) and cumulative deterioration after each irradiation block. The maximum CTR degradation was $> 3\%$. This example of successful deterioration of performance is one core result of the

present campaign. It was shown that using accurately reproduced space radiation in the laboratory with laser-plasma-accelerators, testing is possible making use of adapted standard testing techniques and that significant radiation damage can be exerted on DUTs with these laser-produced radiation belt electrons.

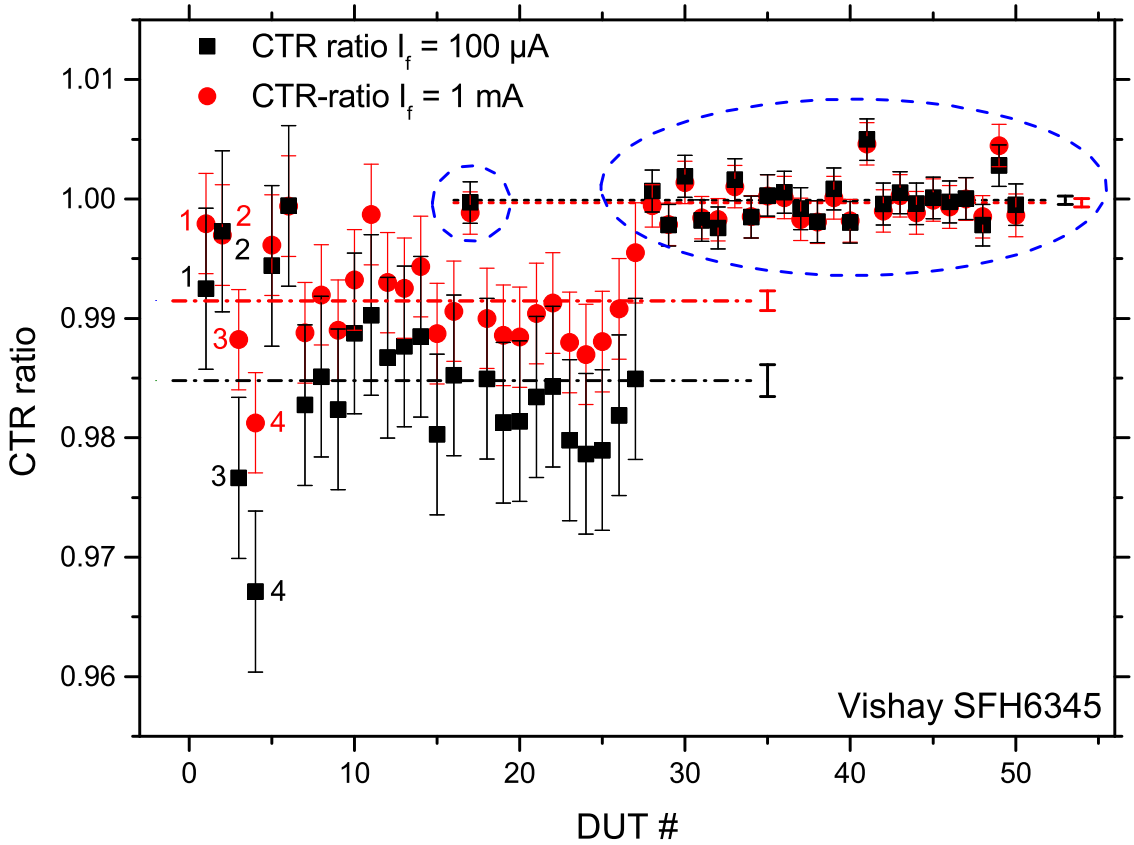

Figure 6: DUT degradation after irradiation: Optocoupler CTR degradation after irradiation with laser-plasma-produced radiation belt flux.

There is one difference between radiation belt flux and LPA-generated flux. Radiation belt flux is quasi-continuous, whereas LPA-generated electron flux is initially pulsed, since it is generated during the laser pulse interaction with plasma electrons. At the source, the duration of the individual electron beams is equal to the laser pulse duration. However, since we have exponential energy distribution, the time of flight of the electrons to the target is massively different for particles with different energies up to ≈ 1 MeV, which leads to a dramatic thinning out and a reduction of peak flux. As an example, figure 7 a) shows the reduction of flux of a LPA-generated beam with $T_{\text{eff}} = 0.35$ MeV, $Q = 100$ nC and a divergence of $\theta = 25°$ through a DUT area of 1 cm^2 after distances of 0.1 cm, 1 cm, and 10 cm. This shows that the peak flux is reduced by more than two orders of magnitude, while the beam is stretched out in time. In figure 7 b) and c), the influence of the finite divergence is illustrated by plotting the flux through the 1 cm^2 test area after 1 cm (b) and 10 cm (c) if zero divergence (dashed line) and if 25° divergence (solid line) are assumed. Here, in a distance of 1 cm from target, most flux still goes through the DUT, while at 10 cm distance, the fraction

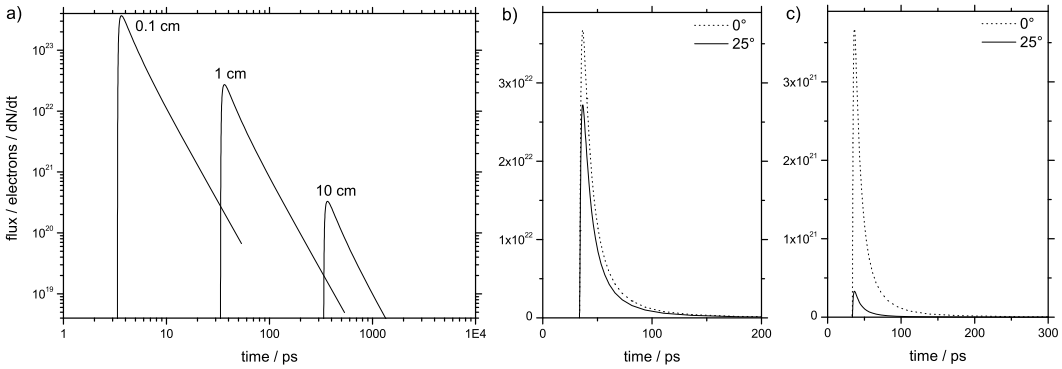

Figure 7: Reduction of exponential-energy electron flux due to energy-dependent velocities and divergence. In a), the flux of a beam with $T_{\text{eff}} = 0.35$ MeV, $Q = 100$ nC and a divergence of $\theta = 25°$ through a DUT area of 1 cm^2 is calculated at distances 0.1 cm, 1 cm, and 10 cm behind target (note the logarithmic scaling). Next, the influence of the divergence is visualized by plotting the flux through 1 cm^2 after a distance 1 cm (b) and 10 cm (c) for the beam with parameters as in a), but for a hypothetical divergence of $\theta = 0°$ and $\theta = 25°$ (from [1]).

on axis which will hit the DUT surface is much smaller as well as the peak flux will be lower.

Relativistic electrons are present in the radiation belts of all five strongly magnetized planets of our solar system, namely Earth, Jupiter, Saturn, Uranus and Neptune [31]. Mainly because the Jovian magnetic field is the strongest planetary field, and Jupiter's rotation is the fastest of all planets, electrons reach highest peak flux and energies in its orbits. Jupiter is currently in the focus of mission planning both for ESA as well as for NASA, for example because of the possibility of life on Jovian moons. The extreme electron flux environment around Jupiter is a major challenge in the context of these missions. According to current models, which were developed after the first measurements of the Pioneer and Voyager probes [32–37], the maximum electron energies in Jovian radiation belts can amount up to 100 MeV, maybe more, at flux levels which can be much higher than in Earth's radiation belts. In figure 8 a), as an example the expected spectral flux is given for two distances around Jupiter, namely at 5 and 9 R_{J}, respectively. It can be seen that the flux at 5 R_{J} could be approximated by an exponential energy distribution. Although the flux at 9 R_{J} cannot be directly described by a single exponential function, it can be approximated by overlaying various different exponential spectra, as is shown in figure 8 b). Here, three different exponential spectra with temperatures of $T_{\text{eff}} = 0.5$, 6 and 32 MeV are used to approximate the actual expected electron flux.

Such high energies and temperatures suggest the use of laser-underdense interaction to reproduce Jovian radiation belt electron flux. In addition, it might be useful to additionally shape the resulting electron flux in a plasma wakefield accelerator stage similar to as described in [38]. The reproduction and shaping of

the extreme electron flux on specific Jovian missions by laser-plasma-interaction is a unique possibility to test space electronics which are chosen for these missions in an unprecedentedly realistic environment. This will potentially increase dramatically the predictability and confidence level in mission component reliability, and could reduce the cost for the missions as aimed at for the next decade.

As a side note, the reader from the laser-plasma acceleration community might find it intriguing to follow us with the idea that the natural acceleration processes which are responsible for electron acceleration at Jupiter [36] are surprisingly similar in many ways to how laser-plasma acceleration works. In fact, in a first step volcanic activities on Jupiter's moon Io ejects gaseous matter into the magnetosphere – the LPA analogue would be a gas jet nozzle. Next, sunlight and secondary electrons ionizes this ejected matter (LPA analogue: the laser pulse). Finally, plasma waves (so called "whistler-mode chorus waves") are excited, which, under proper resonance and dephasing conditions ("gyro-resonance" [36]), can accelerate the electrons to relativistic energies. Future activities are currently in preparation which aim at reproducing outer planets electron environment with laser-plasma-accelerators.

The use of LPAs therefore promises much more realistic testing for these scenarios, and the development of advanced testing procedures, whereby for example for reproduction of the especially harsh Jovian radiation belt electron flux, various beams with varying temperature can be overlayed to approximate the actual spectrum in space. This is similar to advanced treatment plans in particle beam cancer therapy, where different types of particle beams are used to produce the best effect. Due to the initially pulsed nature of LPA-generated electron beams, extremely high peak fluxes can be produced which enable campaigns to determine linear radiation effect thresholds and to increase the understanding of radiation effects, whereby the peak flux can be tuned by varying the distance of sample to target due to the exponential energy and connected particle velocity distribution.

In the proof-of-concept experiments, the focus was put on accurate characterization, monitoring and optimization of the electron flux. The focus was not on application of maximized fluence, which is in principle straightforward, however. In the campaigns carried through in the context of the present project, a number of factors limit the averaged flux and the total fluence:

1. the time needed to break the vacuum to retrieve image plates, to insert new image plates and to evacuate the chamber (approx. 1 hour per irradiation block)

2. the time needed for the image plate readout and erase processes (approx. 20 minutes)

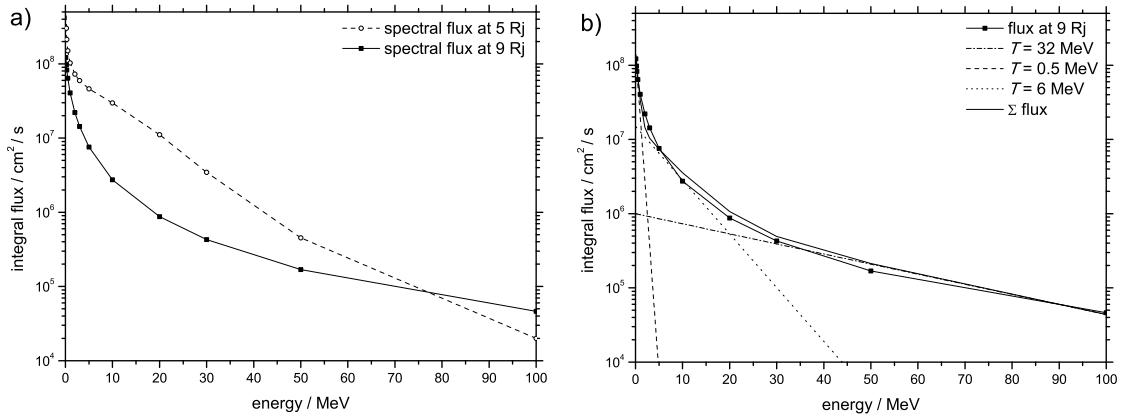

Figure 8: Spectral flux in Jupiter's radiation belt. a) Flux at a distance of 5 R_J and 9 R_J, b) Overlaying three exponential spectra can reproduce with high accuracy the flux expected at 9 R_J (from [1].

3. the time needed to bring the target foil into the Raleigh length of the strongly focused laser pulse (hour-scale)

4. the limited number of shots applicable on one target foil, and the time needed to introduce a new target foil (tens to hundred of shots per foil)

5. the pump performance needed to keep the chamber evacuated during shots

6. the repetition rate of the laser system (currently 10 Hz)

All of these limitations can be overcome already with today's state-ofthe-art technique. This means that the number of shots per time interval, and therefore the averaged flux, can be relatively straightforwardly increased by many orders of magnitude. First, the vacuum does not need to be broken for image plate change because one can relie on the cross-salibrated lanex response for online monitoring, which is thorough enough. Image plates inside the chamber can still be used but need to be more heavily shielded and can then nevertheless provide useful fluence information once the irradiation has ended. Then, the image plate readout process time is consequently also not relevant anymore. Next, positioning of the target foil is much easier when a softer focusing is used. While currently, the Ralyleigh length $z_R = \frac{\pi w_0^2}{\lambda} = 30\,\mu\text{m}$ due to the very sterong focusing with the F/2 parabola, a longer Raleigh length to values beyond 100 microns will dramatically relax the demands put on target positioning. It will furthermore stabilize the radiation output because variations in position do have much less effect on the laser-plasma-interaction. In this connection, and with regard to the maximum number of shots on one target foil, this can be overcome with tape drives. Such tape drives, e.g. consisting of tens of meter long VHS video band, for example, are well-known tools in the laser-plasma-community [39–41]. We have begun construction of a tape drive which is suitable

for space radiation reproduction in the context of the present project (M. Quast et al. at University of Hamburg). An alternative to this if laser-solid-interaction is chosen as underlying acceleration mechanism would be droplet targets, such as described in [42], for example. If laser-underdense interaction is chosen as acceleration mechanism, then a steady-state gas cell with differential pumping would solve the problem of repetition rate. Also, reduced debris as with droplets [42] and underdense targets would subtantially decrease the requirements put on the vacuum system and the pumps. Finally, as regards repetition rate, already today kHz system with many mJ of laserr energy and pulse durations < 100 fs are commercially available. The rapid advance in laser technology has already even produced 100 kHz-level laser systems based on OPA, fibre lasers [43] and thin disk lasers. This trend, and furthermore a much better wall plug efficiency with fiber lasers etc. will continue for the foreseeable future.

It is therefore reasonable to estimate the irradiation time needed with laser-plasma-systems for elevated repetition rates of 10 Hz and belong, which would be seen by future projects, and based on the flux per shot seen in the proof-of-concept experiments. Figure 9 shows that the fluence obtainable per unit time may be dramatically increased with laser-plasma-accelerators when compared to linacs, one assuming a flux of $\approx 1.3 \times 10^8\,\mathrm{e}^-/\mathrm{cm}^2$ (the low flux linac), and one assuming a flux of $\approx 1.2 \times 10^10\,\mathrm{e}^-/\mathrm{cm}^2$ (the high flux linac). It shall be noted that due to the large divergence of laser-plasma-accelerators and the samll source size there is always also the possibility to combine multiple laser systems, e.g. 10 laser systems with 10 Hz repetition rate each, where the laser foci are located close (e.g. on an area of 1 square centimeter or so) such that in a few cm distance the emission cones of these 10 laser systems ovrlap and effectively the flux on the DUT's is increased by an order of magnitude.

4 Summary, Outlook and Roadmap

After the use of laser-plasma-accelerators for space radiation reproduction was proposed in 2010 [19–21], theoretical and design considerations [1] have prepared proof-of-concept experiments which have recently been carried through [22]. They have shown that laser-plasma-accelerators are usable devices to reproduce space radiation in the laboratory and to test damage on electronic components. Laser-plasma-accelerators stand out by their inherent capability to produce broadband particle radiation. Electrons, thanks to their smaller mass, are easier to accelerate than protons and ions, but the energy frontier is continuously pushed, and the maximum electron energies having surpassed 4 GeV with electrons and a few hundreds of MeV with protons. Space radiation is always broadband, which is where one of the intriguing aspects of LPA's for space radiation reproduction stems from. There is a clear scientific trajectory towards

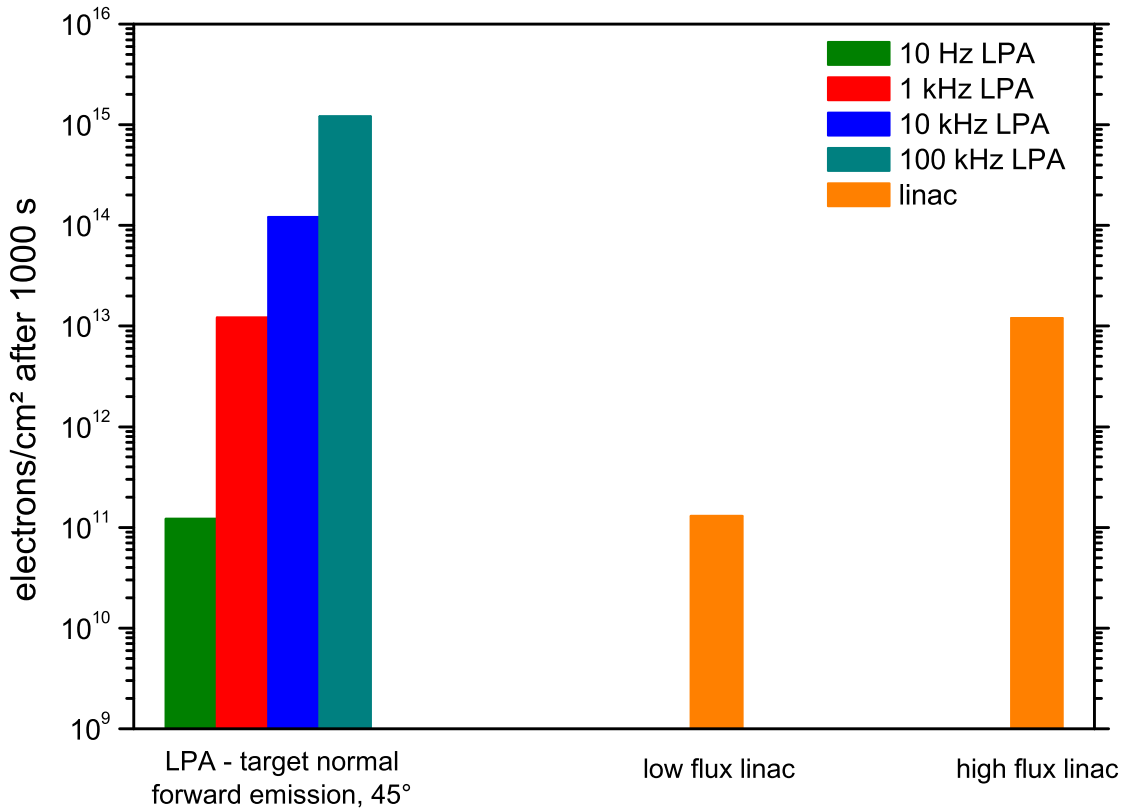

Figure 9: Fluence after 1000 seconds produced with laser systems of different repetition rate when compared to linacs.

the exact reproduction of space radiation not only with Earth radaition belt electrons, but also with the higher energy electron flux in the radiation belts of other planets such as Saturn and Jupiter, which may be a crucial capability for future missions.

This scientific trajectory is being paralleled by ongoing technological progress as regards laser technology, where something like a "Moore's Law" exists. Today's laser systems are already capable to produce 10 Hz repetition rate shots, which are then incident on the electronic test devices in a quasi-continuous flux form due to the broadband spectra and the connected time-of-flight differences which smear out the initially pulsed radiation. There are also laser systems with kHz repetition rate already available which could also be used for space radiation reproduction, thereby increasing the flux accordingly. Laser systems with hundreds of kHz and based on even more compact and efficient technology such as diode-pumped fiber and thin disk lasers do already exist as prototypes and will hit the market in the next years. These systems will further increase the usability and efficiency for space radiation reproduction. They are table-top and can be put even on mobile chassis; this actually was possible already nearly a decade ago, see [44].

Future projects should concentrate on increasing the repetition rate of LPA-based space radiators to 10 Hz and beyond, to reproduce Jupiter-scale radiation

belt flux and to increase the proton and ion energies and flux. The latter could be done in collaboration with large research projects such as the LIBRA consortium or the A-SAIL programme (Advanced Strategies for Accelerating Ions with Lasers) in the UK (2013-2019, 5M£); a recent review can be found in [45].

The computational capabilities to model the generation and expansion of plasma based radiation with particle in cell codes shall be substantially expanded to accompany and optimize future experimential R&D.

The communication between the space radiation testing community and the laser-plasma-accelerator community should be fostered. The space radiation testing comunity holds annual and bi-annual meetings at the Nuclear and Space Radiation Effects Conference (NSREC) [46] and the conference on Radiation Effects on Components and Systems (RADECS) [47]. The laser-plasma-acceleration community does also have various meetings, such as the Advanced Accelerator Concepts (AAC) conference, the Laser and Plasma Accelerator Workshop (LPAW), and is well established as an own research field at overarching accelerator and physics conferences such as the International Particle Accelerator Conference (IPAC) and at the European Physical Society (EPS) conference. It should be considered whether it can be managed to have mutual contributions of both communities at these or other conferences, or even satellite meetings or special topics at these conferences. In the context of the present project, the idea of using laser-plasma-accelerators and first results on space radiation reproduction and testing have already been presented at NSREC and RADECS, where they have triggered broad and intense interest.

It is aimed at establishing a European/worldwide network on the topic of "Plasma-Based Radiation Damages", which would combine laser-plasma-accelerator facilities and groups from the radiation hardness testing community in order to assemble joint projects to further the collaborative R&D in this field. The motivation for the space radiation industry would be a) the prospect of getting additional beamtime provided by such appliation oriented plasma accelerator facilities such as the Scottish Centre for the Application of Plasma-based Accelerators SCAPA or sites of the European Extreme Lights Infrastructure ELI, b) the prospect of having and maintaining small laser-plasma-accelerators on site directly where the missions are planned or the electronics are developed, c) having much more accurate and meaningful test results by using exactly reproduced space radiation d) decreasing the test times by having much higher flux from high rep rate LPA's and/or an array of LPA's, and e) the access to dramatic particle peak flux otherwise not accessible with conventional accelerators, while on the other hand for the laser-plasma-accelerator the space radiation-like broadband particle flux reproduction would be a highly welcome application which can have short-term industrial application as the production of broadband radiation is a comparably low-hanging fruit.

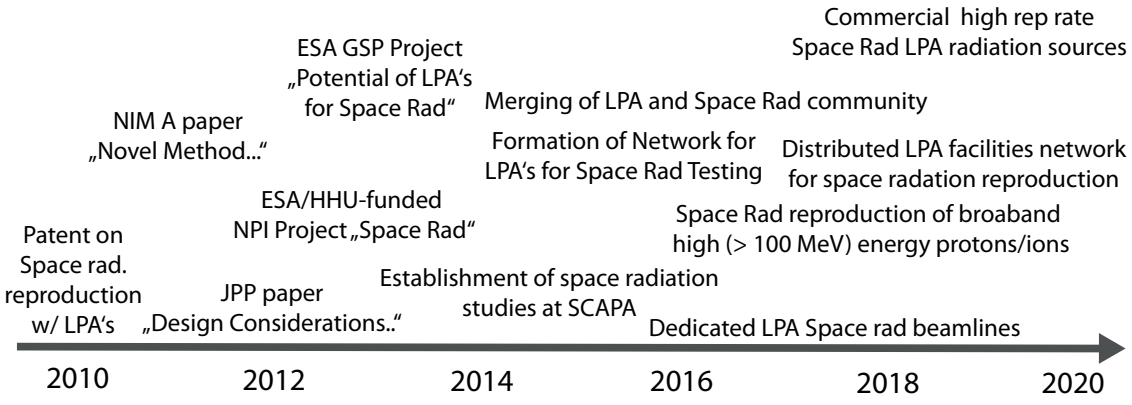

Figure 10: Roadmap for the development of laser-plasma-accelerator based space radiation reproduction and testing.

Figure 10 shows a draft roadmap for the further development of laser-plasma-based space radiation tests, which has been compiled in the context of the present project. The roadmap extends until 2020. Looking in the past, the whole field was triggered by the patent on space radiation reproduction with laser-plasma-accelerators, filed in Germany [19] and then later in the US by Radia-Beam Technologies [20], which already indicates the huge industrial relevance. Shortly after the patent, a paper summarizing the basic idea and prospects was published [21]. These theoretical considerations were then consolidated in the ESA seed project [22], published in peer-reviewed form in [1], and first proof-of-concept experiments have been successfully carried through [22], the highlights of which are presented in this GSP report. Supported by these encouraging results, the idea is getting traction within the plasma community, and currently space radiation studies are being implemented at SCAPA, for example. The future will hopefully see increased network building, combining the radiation effects and the plasma accelerator community. Europe has an especially strong position as regards available laser-plasma-accelerator facilities. Further high-power laser systems are mushrooming all over the Agency's member states and in the world, which may give Europe a head start in further exploiting the potential of laser-plasma-accelerators for space radiation reproduction. The accessible particle flux, fluence and energy regimes should be consequently expanded for example producing protons and ions in excess of 100 MeV/a. Dedicated space radiation beamlines at plasma accelerator facilities may be the result of this, and maybe a distributed nework of space radiation laser-plasma facilities as part of the European Radiation Test Facilities network. At the same time, the laser technology improvements as regards higher rep rate and power, and further miniaturization may lead to ultracompact, mobile devices and commercial turnkey systems until 2020.

5 Acknowledgements

Support from the following organizations and scientists is gratefully acknowledged: European Space Agency and Heinrich-Heine-University Düsseldorf for funding of this Networking Partnership Initiative; BH thanks Forschungsfoerderungsfonds Heinrich-Heine-University for additional research group funding; RadiaBeam Technologies, Santa Monica, USA, and UCLA for R&D contributions and patenting support; Toma Toncian, Monica Toncian, and Oswald Willi for an excellent Arcturus laser performance and technical support during various space radiation beam time campaigns; proton irradiation and image plate testing at UCL, Belgium; A. Costantino, E. Daly, V. Ferlet-Cavrois, S. Hernandez, and G. Santin at ESTEC/ESA; R. D. Harris, P. Adell, H. Schoene, S. McClure, L.Z. Scheick, and J. Insoo at Jet Propulsion Laboratory/NASA; computational support from A. Karmakar at Leibniz Computing Center Munich, and computational resources at NERSC Berkeley, HLRN, and JUROPA. In the context of this work, one PhD thesis (T. Königstein, 2013), one master thesis (O. Karger, 2013) and three peer-reviewed Journal publications (a) Bernhard Hidding, Thomas Koenigstein, Oswald Willi, James B. Rosenzweig, Kazuhisa Nakajima, and Georg Pretzler. Laser-plasma-accelerators–a novel, versatile tool for space radiation studies. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 636(1):31 – 40, 2011, b) T. Koenigstein, O. Karger, G. Pretzler, J. B. Rosezweig, and B. Hidding. Design considerations for the use of laser-plasma accelerators for advanced space radiation studies. Journal of Plasma Physics, 78:383–391, 8 2012) have already been published, others are in preparation. The concept has been patented (B. Hidding, T. Königstein, O. Willi, G. Pretzler. Method for testing the radiation hardnessof electronic devices with particle and photon beams generated by laser-plasma-interaction.German Patent AZ 10 2010 010 716.6, March 2010. Filed on March 8, 2011 as extended United States patent in collaboration with RadiaBeam Technologies, Santa Monica, Method for testing electronic components, Serial No. 13/042,738). This report is partially based on the above mentioned publications and theses and includes text and figures from those references.

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