Radiobiology experiment design and modeling for space applications at ELI-NP

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Abstract: *Space radiation fields are mixed radiations with broadband energy spectra that will affect astronauts health during deep space missions or in permanent human habitats on Mars. Solar flares are large, unpredictable, explosive events consisting of accelerated protons and electrons with an energy around 100 MeV and up to 10 GeV. Relevant radiation backgrounds were reported in the literature and measured with the Mars Science Laboratory during a cruise to Mars plus an additional 500 days stay on the Martian surface. The total dose was estimated at 1.01 Sv, while ESA career dose limit is also 1 Sv. To find adequate countermeasures to chronic exposure to multi-energetic, mixed radiation fields, more radiobiology experiments are necessary. At ELI-NP research facility, such mixed radiation fields could be obtained through the interaction of two high power lasers (1PW, 25 fs each) with solid or gaseous targets that can generate pulsed proton or electron beams, gamma- and X-rays. Mimicking the space radiation would become possible by overlapping these beams on the same biological sample. In addition, the laser accelerated particle beams have broadband spectra, unlike radiation obtained with classical accelerators. An experimental irradiation set-up and preliminary Geant4 dose estimations for a laser accelerated proton beam will be presented.*

Key Words: *radiobiology, laser-driven proton beam, experimental setup, dose estimations, Geant4 simulations*.

1. INTRODUCTION

There is an increased interest and plans for long term space missions and building of permanent extra-planetary bases with human crews. However, it is recognized that there is an increased risk of chronic radiation exposure and health consequences from travel through intense space radiation fields, [1]. For instance, solar flares are large, unpredictable, explosive events consisting of accelerated protons and electrons with an energy around 100 MeV and up to 10 GeV, [2].

Radiation backgrounds were also measured with the Mars Science Laboratory, [1] during a cruise to Mars plus an additional 500 days stay on the Martian surface. The total dose was estimated at 1.01 Sv, while ESA career dose limit is also 1 Sv. Therefor a number of space and ground based laboratories are trying to measure and quantify as accurately as possible the radiation levels and health effects caused by the high radiation doses experienced by astronauts in long term missions.

Currently the existing radiation sources mimicking the space radiation can provide only mono-energetic spectra. Recently with the development of high power lasers a new type of particle acceleration is possible.

First results in laser-generated radiation have been reported in the literature less than two decades ago [3,4]. Proton and ion acceleration is possible through a mechanism called Target Normal Sheath Acceleration (TNSA), [5] which in principle occurs at the interaction of a focused high power laser with a solid target that has a thickness of the order of hundreds of nm up to tens of microns. Other mechanisms are also being investigated as Radiation Pressure Acceleration (RPA), [6] and Break -Out After-burner (BOA), [7]. Due to an increase in the number of high power laser facilities around the world, the laser accelerated particles will play a higher role in the future assessments of space radiation effects, especially that their energetic spectrum is exponential, similar to those of radiation fields in the outer space.

One of these high power laser facilities is Extreme Light Infrastructure - Nuclear Physics (ELI-NP) that will host two 10 PW, two 1 PW and two 0.1 PW lasers, based on the Ti:sapphire technology, capable of generating ultrashort pulses (25 fs) with a pulse repetition rate of 1/60, 1 and 10 Hz, respectively. The 1 PW laser at ELI-NP will be dedicated to obtain secondary sources of radiation including protons, ions, electrons, X-ray and gamma rays.

Recently a group at CoReLS in South Korea has reported the obtaining of a proton beam accelerated to a maximum energy of 93 MeV using a laser system similar to that from ELI-NP, [8]

The same group was successful in accelerating electrons with energies up to 3 GeV, using a gas jet, [9]. A laser-target interaction chamber (2 m diameter) in the experimental area E5 at ELI-NP will be dedicated to irradiation experiments of materials in extreme environments and of biological samples, for space and medical applications.

After low- or high - dose, single-shot or multiple irradiations, the biological samples consisting in normal and diseased cell monolayers or ex-vivo tissue will be studied for radiobiological effects, using an array of methods, including direct and indirect effects, as well as proteomic and genomic approaches.

In this paper we present an experimental design for in-vitro irradiation experiments of cell monolayers in a standard 96 well plate.

In order to accommodate the cells at physiological conditions while irradiation takes place inside the laser target interaction chamber, we have designed a vacuum-sealed Al cassette to host the well plate and to control the temperature.

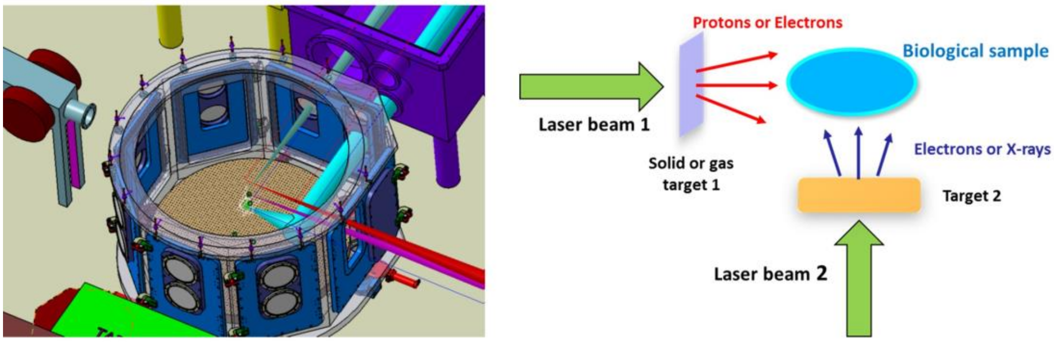
Geant4 modeling of radiation transport through the various components of the setup and dose deposition in the cell monolayer has been performed and results are presented in this paper.

2. EXPERIMENTAL SETUP DESIGN

In order to perform irradiation experiments of biological samples at ELI-NP it is necessary to obtain reproducible pulsed particle beams (secondary beams), through the interaction of two 1 PW lasers with a thin solid target and a gas target respectively (primary interaction), inside a vacuum chamber, designed for the experimental area E5 and shown in Fig. 1a.

In this schematic, several laser beam configurations are possible. In the case of the laser arm interacting with the solid target the beam is focused by means of a short focal length off-axis parabola placed inside the interaction chamber. For the gas target the laser beam focusing is obtained with a long focal length off-axis parabola placed outside the interaction chamber.

In Fig. 1b the general concept of irradiation of biological samples with a "cocktail of radiation" (mixed radiation fields) is presented.



a b

Fig. 1 – a) Schematic of the laser-target interaction chamber (experimental area E5) and laser beam configurations inside the chamber; b) schematic of concept of simultaneous irradiation of biological systems with laser generated particle beams

Two types of secondary irradiation beams could be obtained: 1) with a broad energetic spectrum inside the interaction chamber for space applications and 2) collimated mono-energetic beams transported outside the interaction chamber, suitable for medical applications. Beam characterization will be achieved by online and offline diagnostic systems (eg. Thompson parabola, high- energy electron spectrometer, radiochromic films (RCF) and imaging plates (IP)).

Cell monolayers placed in a standard 96 well plate will be inserted in a vacuum sealed Al cassette with Al or Ni window, as shown in Fig.2. The cassette will allow temperature control and physiological conditions for biological material. A target and sample insertion system was designed and built to automatically place the Al cassette in the interaction chamber and position it on a five degree-of-freedom sample positioning stage, shown in Fig. 3.

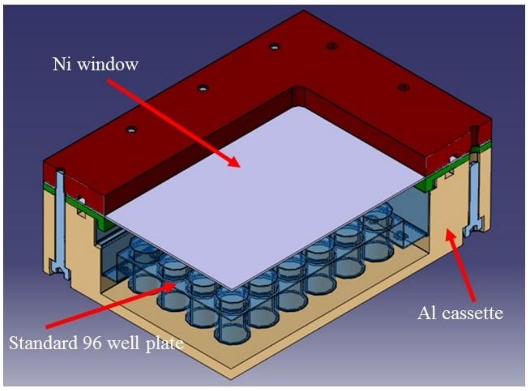


Fig. 2 – Vacuum sealed Al cassette hosting the standard 96 well plate with biological samples

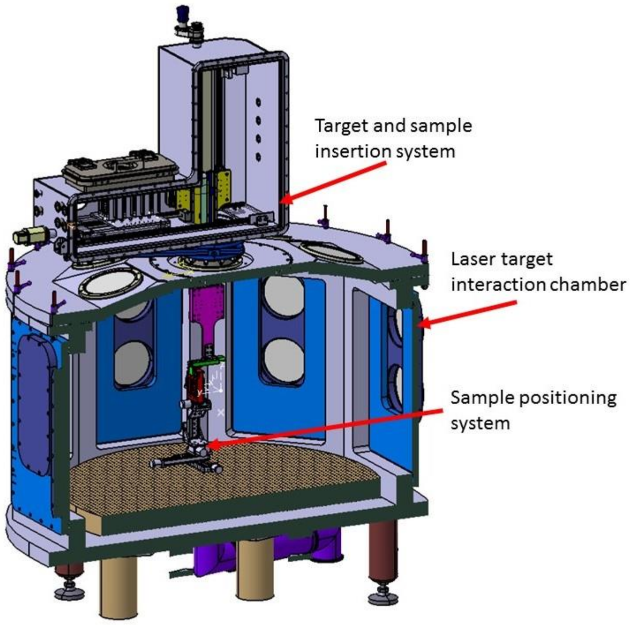


Fig. 3 – Target and sample insertion/positioning system integrated with the interaction chamber

3. GEANT4 MODELING AND RESULTS

A geometry similar to the designed Al cassette with the 96 well plate inside was built in a Geant4 simulation and calculations of the deposited energy in the cell monolayer (10 µm thick) from a proton beam of maximum energy of 30 MeV, 30 degrees divergence, with a uniform angular distribution, [10] were performed.

The distance between the proton source and the Al window (0.5 mm thickness) of the cassette was 30 cm. The standard 96 well plate was positioned such that two air layers, each of 0.5 cm thickness were present in front and behind the plate.

The orientation of the 96 well plate was in a vertical plane, with the bottom of the plate towards the Al window (and the proton source) in order to allow irradiation of cells through only a thin layer of polystyrene (1 mm). In experiments involving a 96 well plate (regardless its spatial orientation, the cell monolayer is covered by a 0.9 cm thick layer of cell culture media, and if necessary, this allows sealing of the plate with a polyethylene thin film.

In the simulations, the protons were sent from the source towards the cell monolayer, one by one, up to 10^{10} particles and the results were scaled up to 10^{12} protons.

The proton interactions in various materials along the travel path were modelled using the Shielding Reference Physics List.

An attenuator with variable thickness (tile-shaped) shown in Fig. 4, was designed and included in the Geant4 simulation between the proton source and the cell monolayer.

The role of this attenuator is to ensure a uniform deposition of proton energy inside the cell monolayer, in each well and over the whole plate.

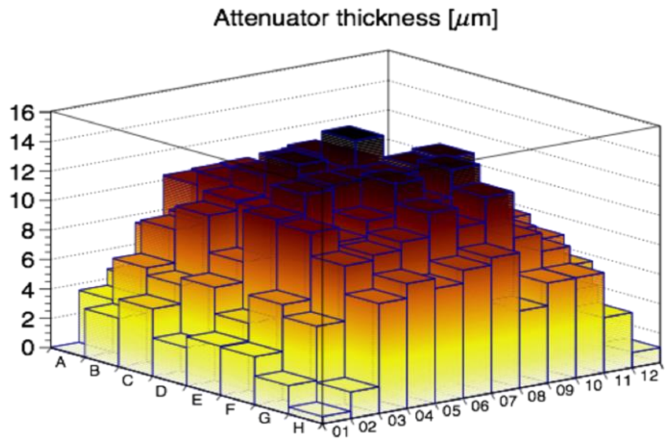


Fig. 4 – Tile type attenuator for a uniform deposition of proton energy inside the cell monolayer (tile section 9 mm x 9 mm)

The deposited energy was calculated as a Geant4 output in each mesh element (20 µm x 20 µm x 20 µm). There were approximately 8×10^4 mesh elements in each well. The total number of events (proton sent from the source) was 10^{10}.

The corresponding dose was computed as the energy deposited in one well divided by the cell monolayer's mass in one well.

The diameter of each well was 6.3 mm. Distribution of deposited energy in the cell monolayer over the whole 96 well plate with and without an attenuator is shown in Fig. 5a and 5b. The dose variability on the plate of 8.5% from average dose without an attenuator and 1.3 % with the attenuator.

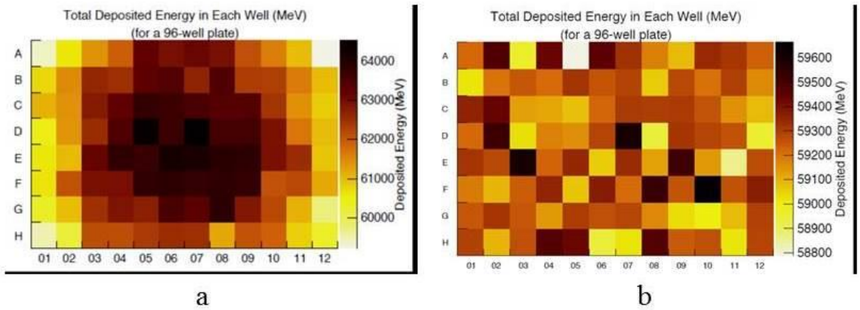


Fig. 5 – Distribution of energy deposited in a cell monolayer by a proton beam with maximum energy 30 MeV: a) without an attenuator; b) with an attenuator of variable thickness.

The calculated dose was 0.01 Gy for a total number of protons of 10^{10} and the value was scaled up to 1 Gy for 10^{12} protons per pulse.

4. CONCLUSIONS

Geant4 simulations were performed to investigate the distribution and values of the energy deposited in a cell monolayer using a proposed experimental setup that allows biological sample irradiation inside a vacuum chamber with pulsed proton beam generated by fs lasers, similar to those at ELI-NP. The proton beam obtained with a high power laser can better simulate in a ground based laboratory the spectrum of space radiation fields, for example a solar proton event (SPE). The dose distribution is not uniform over the 96 well plate hosting the cell monolayer, but a variable thickness tile-type attenuator placed between the proton source and the cell monolayer provides dose uniformity and a dose around 1 Gy for a total number of protons per pulse of 10^{12}. The value of 1 Gy is a reasonable dose value for in-vitro irradiations and single shot or repeated irradiation could be performed.

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REFERENCES

[1] D. M. Hassler, C. Zeitlin, R. F. Wimmer- Schweingruber, B. Ehresmann *et al*. Mars' Surface Radiation Environment Measured with the Mars Science Laboratory's Curiosity Rover, *Science*, **343** (6169), 1244797, 2014.

[2] R. A. Mewaldt, M. D. Looper, C.M.S. Cohen, G.M. Mason, D.K. Haggerty, M.I. Desai et al., Solar-Particle Energy Spectra during the Large Events of October-November 2003 and January 2005, *29th International Cosmic Ray Conference, Pune (2005,)* **00**, 101-104, 2005.

[3] E. L. Clark et al., Measurement of energetic proton transport through magnetized plasma from intense laser interactions with solids, *Phys. Rev. Lett.*, vol. **84**, 670, 2000.

[4] R. A. Snavely et al., Intense high-energy proton beams from petawatt-laser irradiation of solids, *Phys. Rev.Lett.*, vol. **85**, 2945, 2000.

[5] M. Passoni, L. Bertagna and A. Zani, Target normal sheath acceleration: theory, comparison with experiments and future perspectives, *New Journal of Physics*, vol. **12**, 045012, 2010.

[6] A. Macchi, S. Veghini, T. V. Liseykina and F. Pegoraro, Radiation pressure acceleration of ultrathin foils, *New Journal of Physics*, vol. **12**, 045013, 2010.

[7] L. Yin, B. J. Albright, B. M. Hegelich and J. C. Fernandez, GeV laser ion acceleration from ultrathin targets: The laser break-out afterburner, *Laser and Particle Beams*, vol. **24**, 291-298, 2006.

[8] I. J. Kim et al., Radiation pressure acceleration of protons to 93 MeV with circularly polarized petawatt laser pulses, *Physics of Plasmas*, vol. **23**, 070701, 2016.

[9] H. T. Kim et al., Enhancement of Electron Energy to the Multi-GeV Regime by a Dual-Stage Laser-Wakefield Accelerator Pumped by Petawatt Laser Pulses, *Physical Review Letters*, vol. **111**, 165002, 2013.

[10] J. S. Green, A. P. L. Robinson, N. Booth, D. C. Carroll, R. J. Dance, R. J. Gray et al., High efficiency proton beam generation through target thickness control in femtosecond laser-plasma interactions, *Appl. Phys. Lett.*, **104**, 214101, 2014.