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Biological Effect of Space Radiation Simulated at Ground Base Plasma Facility

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Abstract

Schemed with high repetition rate, the plasma focus device promises to simulate the radiation environment and analyze the biological effects on cells. The most radiation-sensitive site within the cell, DNA, could be irradiated by 110 j proton beams at high operation frequency. Such plasma device if operated at 1 Hz repetition rate produces ten Double-Strand breaks, DSB, per second. The surviving fraction of the DNA is likely to be more affected by higher dose frequencies.

Keywords: Repetition rate; Biological effects; DNA; Double-Strand breaks

Introduction

The research to analyze "biological effect at ground base facilities", where the space radiation environment can be simulated, helps to understand and reduce the radiation risk to ensure proper measurement of doses received by space travelers and to develop advanced materials that improve radiation shielding for space exploration [1].

Plasma focus (PF) as a pulsed plasma device generates intense, bright, and energetic beam of protons. The spectrum starts with very high energy ions in a small spot and continues with the spectrum which represents the lower energy ions distribution [2-4]. Typical ion spectrum of the low energy PF device presents an average energy of about 40 keV, followed by a high energy tail of a few MeV. The proton beam current of about 100 kA provides an appropriate test bench to irradiate relevant targets.

Proton beam of a low energy PF enables simulation of radiation induced DNA damage and if operated at high repetition rate, facilitates analysis of the damaged DNA surviving probabilities.

Proton beam plasma source

In the pulsed plasma systems, the Lorentz forces are applied to an ionized gas through the interaction between a large current discharge and the induced magnetic fields. Capacitive stored energy is abruptly switched across the electrodes assembly separated by ambient gas in the pressure range of a few mbar. The gas breaks down and the current rises rapidly in the circuit followed by thin current sheet formation with a minimum inductance configuration. The magnetic field enclosed by the circuit, accelerates the current sheath through the ambient gas, as a result of interaction with the discharge current. Sheath then collapses on the axis and a compressed plasma column, pinch, is formed. Plasma focus device does not require any kind of external magnetic field and efficiently uses the magnetic energy presented in the plasma column. PF is the most powerful laboratory source of the plasma radiations. High energy density and very strong magnetic field enables a broad spectrum of phenomena to be occurred within the PF, among them is the ion/electron acceleration to MeV range energies [8-11].

Accelerated ions in the PF are produced by rapid diffusion of azimuthal magnetic field toward the electrodes axis. Afterward, there is a sharp change in the plasma inductance generating an axial electric field. The experimental ion energy spectra display decreasing intensity with increasing energy.

Double-Strand Breaks, DSB, is one of the categories of radiation-induced chemical changes to DNA that result in damage to the structure of the DNA. The production, and repair/mis-repair of DSBs are of great importance to understanding radiation-induced cell lethality. The basic kinetics of the induction of radiation-linked DSBs suggest that the number of repaired DSBs during a specific time interval is proportional to the total number of DSBs. However, operating the proton source at high repetition rates dismisses the possibility for cell to be survived [5-7].

Analysis

The first step in the analysis of induced DSB is to determine the dose deposition in the DNA. A simple approach to calculating the proton beam energy would be to make use of Langmuir-Child law for a low energy PF facility. NX2 device is the lowest bank energy PF for which intense high energy ion beams have been observed [12]. Pinch voltage U of the NX2 for Ip=220 kA and rp=1.46 mm is estimated to be ~40 kV. Then the proton beam energy is approximately calculated from:

$$E_i = K_1 U^{5/2} \frac{\tau}{r_p^2} = 110j \qquad \text{Eq. 1}$$

Where □1 = 5.44 × 10−8 for protons, and the acceleration period □ = 12□. Ei for low to medium energy PF devices, less than 50 kJ, approaches 103 j with a steep slope. A power law fit is performed with the experimental data to determine the linear relationship between proton beam energy and the PF bank energy as: □□ ∝ □1.17

The radiation dose by 110 j proton beam deposited on the DNA with the dimension of 2.5 nm is estimated to be ~0.25 Gy per PF bank discharge. It is worth noting that the prescribed dose for radiation therapy treatment is 2 Gy [6] (Figure 1).

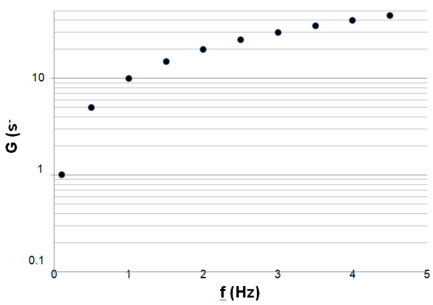

Figure 1: DSB rate at operation frequencies.

The DSB yield for a 40 keV proton beam -the average energy in the proton spectrum of NX2 device- is 25 Gy-1 cell-1 [13].

Then the minimum value of proton beam energy for one DSB per discharge is ~10 j.

The NX2 device is a high repetition rate PF capable of operating at 16 Hz [14].

Consequently the DNA target can be irradiated by 16 proton beams each carrying 110 j of energy at one second. The DSB rate is:

$$G = \delta f D \qquad \text{Eq. 2}$$

where f is the discharge frequency, D is the measured dose per discharge, and is the dose rate efficiency which is 40 DSB/Gy [5]. This shows the DSB rate for NX2 device; if operated at 1 Hz, it produces 10

DSB/s.

Taking intrinsic DNA repair half-life to be 2-10 min [14], then the potential DSB rate, I, is:

$$\frac{dI}{dt} = \frac{-dR}{dt} I - \frac{dx}{dt} I \qquad \text{Eq. 3}$$

where R is the repair term and x is the lethal lesion term. Solving Eq 3 for potential DSB yields an exponentially decreasing function of the form:

$$I = I_0 e^{-(A+B)I}, \qquad A = \frac{dR}{dt}, B = \frac{dx}{dt} \qquad \text{Eq. 4}$$

Since R>>I, R in min and I in ns time scales, then potential DSB is considered the de facto DSB, lethal lesion. Then the surviving fraction, S, of damaged DNA is:

$$S = exp(-I) \qquad \text{Eq. 5}$$

This shows that even a small change in the dose frequency, drastically alters the surviving probability of the DNA.

For instance, S is in the order of 10-5 at 1 Hz, Fig 2a, and 10-9 at 2 Hz, Fig 2b.

From practical point of view, this would be of great importance if the operation frequency of the PF device increases.

Therefore, the higher the operation frequency, the greater the absorbed dose in the DNA.

For a lethal lesion interval of 0.3-10 Gy-1 cell-1 [5], the PF generates 0.07-2.5 lethal lesion per cell (Figure 2).

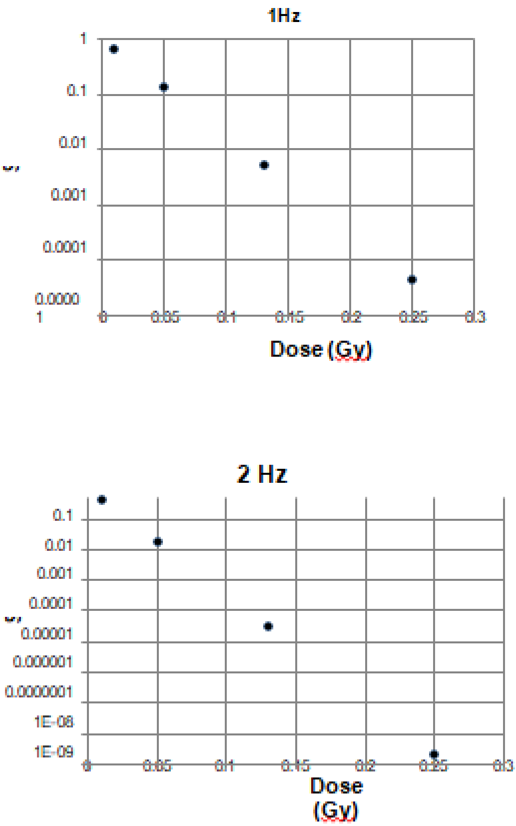

Figure 2: Surviving fraction of the DNA at 1 Hz (up) and 2 Hz (down).

Conclusions

Low energy plasma focus provides ground based facility to analyze the Double-Strand breaks, DSB, induced by proton beam irradiation of the DNA. The radiation dose by 110 j proton beam on the DNA with the dimension of 2.5 nm is ~0.25 Gy per discharge. Dose frequency shifts substantially the surviving probability of the DNA toward the lowest possible values. The surviving fraction is in the order of 10-5 at 1 Hz and 10-9 at 2 Hz for NX2. Low energy PF device generates 0.07-2.5 lethal lesion per cell.

Author Contribution Statement

All authors contributed equally to the paper.

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