Demonstration for Inactivation of Zooplankton by Irradiation with a Pulsed Intense Relativistic Electron Beam

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Zooplankton contained in water have been successfully inactivated by irradiation with a pulsed intense relativistic electron beam (PIREB). A treatment chamber is filled with a solution of 3-wt% salt in water containing Artemia larvae as zooplankton samples and is irradiated using the PIREB (2 MeV, 0.4 kA, 140 ns). We found that up to 24% of the Artemia are inactivated by firing 10 shots of PIREB irradiation.

Keywords: pulsed intense relativistic electron beam (PIREB), ballast water, pulsed power, zooplankton, ocean ecosystem

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Ships such as cargo ships use ballast water to stabilize their hulls during navigation. The ballast water is carried around the world and is dumped at a port of call, causing an undesirable propagation of microbes, bacilli and eggs and larvae of marine organisms and the growth of marine plankton in ocean ecosystems. To conserve the ocean environment, a convention was adopted by the International Maritime Organization in 2004 [1]. It specifies that ships must manage their ballast water by using devices such as a ballast water treatment device, not later than 2016. Some methods of treating the water, such as pulsed power electrical discharge [2], have been studied. At present, however, each and every method has technical, financial, and environmental problems.

In the present study, we propose a new method of treatment which uses irradiation by a pulsed intense relativistic electron beam (PIREB). In this method, chemicals and/or additives are unnecessary for treatment. The purpose of this paper is to investigate the properties of PIREB injection into ballast water and the effects of irradiation by the PIREB on zooplankton. The PIREB with a kinetic energy of up to 2 MeV is generated using a field-emission foilless electron-beam diode, in which a hollow cathode and a ring anode are set at the first acceleration cell of the pulsed power generator ETIGO-III [3]. The diode gap is vacuumed to 0.02 Pa.

Figure 1 shows a side view of the treatment chamber for PIREB irradiation. The chamber was made of a polypropylene pipe with an inner diameter of 110 mm,

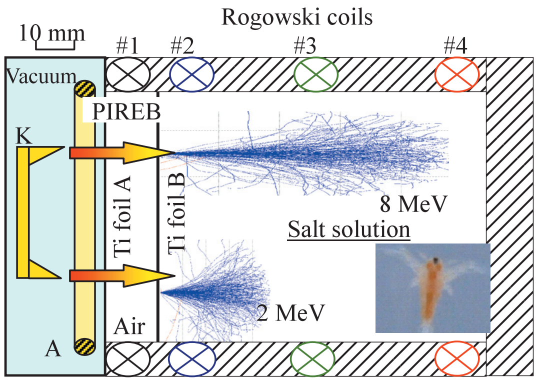

Fig. 1 Side view of treatment chamber. Simulated electron trajectories are also indicated.

a length of 86 mm, and a capacity of 0.8 L, where an end flange of the chamber was floated from the ground. The chamber was separated from the vacuum part of the electron-beam diode by an air bulkhead and was filled with a 3-wt% salt solution as ballast water. The salt solution was made from distilled water and common salt. Artemia larvae were added to the salt solution as zooplankton.

Figure 1 also shows the measurement setup for the PIREB. The irradiated and injected PIREB current in the salt solution was measured with Rogowski coils placed at the inlet (#1), front (#2), middle (#3), and end (#4) of the treatment chamber. Rogowski coil #1 was placed at the front of titanium foil B and the coils #2, #3, and #4 were placed behind titanium foil B at a distance of 5 mm,

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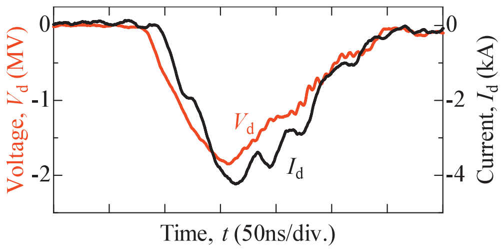

Fig. 2 Time evolution of voltage (V_d) and current (I_d) at electron-beam diode.

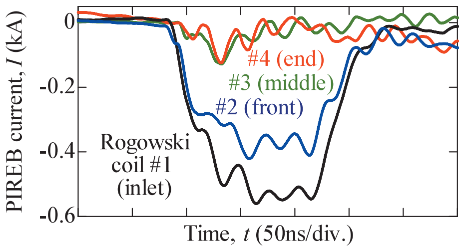

Fig. 3 Time evolution of PIREB current in treatment chamber at various positions.

35 mm, and 77 mm, respectively.

The zooplankton, Artemia larvae, were observed using a stereoscopic microscope. We assumed that the Artemia larvae that stop moving in one minute were inactivated because of irradiation.

Electron trajectories in the solution simulated using the CASINO program [4] are also shown in Fig. 1. The maximum penetration depth of 8-MeV electrons was found to reach 70 mm. Although the depth was reduced to 17 mm for 2-MeV electrons, the electrons spread over 30 mm. This indicates that the 2-MeV PIREB is suitable for treatment over a large area.

Figure 2 shows the typical time evolution of the electron-beam diode voltage (V_d) and current (I_d). Results show that the V_d and I_d corresponding to the acceleration voltage and the beam current of the PIREB reach −2 MV and −4 kA within 70 ns.

Figure 3 shows the typical time evolution of the PIREB current in the treatment chamber. The results indicate that a PIREB with a current of −0.55 kA was irradiated into the chamber. We also estimated that the current injected by the PIREB into the solution was more than −0.4 kA. Because the PIREB deposits energy within the solution, the current decreased drastically at the middle and end of the chamber.

To accurately determine the characteristics of zooplankton inactivation in the treatment chamber, the inactivation rate of the Artemia larvae was observed without PIREB irradiation. The inactivation rate is defined as (Number of inactivated Artemia/Total number of Artemia) × 100 (%).

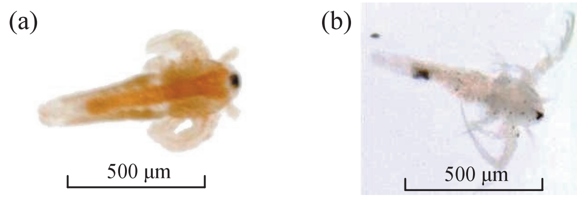

Fig. 4 Example of Artemia larvae (a) before irradiation and (b) after irradiation.

Table 1 Inactivation rate of Artemia as a function of time without PIREB irradiation.

Time, t (min)	Inactivation rate (%)
10	0-2
65	0-4

Table 2 Inactivation rate of Artemia with one shot of PIREB irradiation.

Total number of Artemia	Number of inactivated Artemia	Inactivation rate (%)
41	1	2
45	1	2
42	2	5
48	2	4
42	1	2

Table 3 Inactivation rate of Artemia with 10 shots of PIREB irradiation.

Total number of Artemia	Number of inactivated Artemia	Inactivation rate (%)
46	11	24
44	5	11
43	6	14
43	8	19
40	9	23

Table 1 shows the inactivation rate as a function of time. Here, 50 Artemia larvae were contained in the solution and remain during the specific time t. Here, the t values of 10 and 65 minutes correspond to the minimum time required for irradiation by using one and 10 shots of PIREB irradiation, respectively. Few Artemia larvae were inactivated without PIREB irradiation.

Figure 4 shows the state of the Artemia larvae before and after PIREB irradiations. The Artemia move their legs actively and swim in the solution before irradiation (see Fig. 4 (a)), whereas the inactivated Artemia turn pale and stop moving after irradiation (see Fig. 4 (b)).

Tables 2 and 3 show the inactivation rates of the Artemia larvae with one and 10 shots of PIREB irradiation, respectively. No increase in the inactivation rate is found with one shot of PIREB irradiation compared to that without PIREB irradiation at $t = 10\,\mathrm{min}$. On the other hand, with 10 shots of PIREB irradiation, the inactivation rate is in the range of 11–24%. This indicates that the zooplankton are successfully treated using PIREB irradiations.

In conclusion, we have demonstrated that the inactivation rate of zooplankton can reach 24% by firing 10 shots of PIREB irradiation. Increasing the inactivation rate and elucidating the mechanism of the inactivation are the subjects of our future study.

[1] GloBallast, http://globallast.imo.org/
[2] Z. Li *et al.*, IEEE Trans. Plasma Sci. **34**, 1719 (2006).
[3] A. Tokuchi *et al.*, Proc. 12th Int'l Conf. on High Power Particle Beams, (1998) p.175.
[4] D. Drouin *et al.*, Scanning **29**, 92 (2007).