§2. Optimization of Phase Velocity of Traveling Wave in a TWDEC Simulator

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Traveling wave direct energy converter (TWDEC) is expected to recover energy of fast proton in D–^{3}He fusion. The authors are continuing fundamental experiments of TWDEC using a small size simulator$^{1)}$. In the research on beam deceleration, the simulator works in the active decelerator mode$^{2)}$, in which traveling wave in the decelerator is excited externally.

As the beam deceleration is enhanced, mismatch between the beam velocity and the phase velocity of traveling wave becomes significant. In order to achieve the complete matching between them, an optimized structure of the decelerator was designed. For single particle deceleration, the phase velocity of traveling wave ($v_\phi(z)$) is expressed by

$$\frac{v_\phi(z)}{v_{\phi 0}} = \left\{1 + \frac{3}{2}\frac{E_{\rm M0}}{V_{\rm ex}}z\right\}^{1/3}, \qquad (1)$$

where z is an axial coordinate in which the origin is at the entrance of the decelerator. $V_{\rm ex}$ is an initial beam energy in the unit of eV, and $E_{\rm M0}$ and $v_{\phi 0}$ are the wave field strength and the phase velocity of the wave at $z = 0$, respectively.

We realized the axial variation of the phase velocity expressed by Eq. (1) in two ways. One was using an electrode array aligned with the same distance$^{1)}$. We varied relative phase difference between electrode voltages by adjusting the length of delay lines between electrodes, which was schematically shown in Fig. 1. By designing the length of delay lines according to Eq. (1), we can optimize the decelerator structure. The other way was to adjust the distance between electrodes with keeping the relative phase difference between electrode voltages constant. The amount of adjustment can be also derived from Eq. (1).

The experiments were performed with the setup shown in Fig. 1. The results are summarized in Fig. 2 with the results of 1-D numerical calculation$^{1)}$. The abscissa of Fig. 2 is a normalized length of the decelerator. An actual length of the decelerator $L_{\rm D}$ is normalized by the maximum length of the decelerator $L_{\rm DM}$, which is determined by the condition that the argument of cubic root of Eq. (1) is positive. The ordinate of Fig. 2 is deceleration efficiency for unit wavelength η_1. Open and closed circles indicate experimental results for axially varied v_ϕ and fixed v_ϕ, respectively. The previous results of fixed v_ϕ in the low beam energy are also presented by closed triangles. The results of 1-D numerical calculation for varied v_ϕ and fixed v_ϕ are indicated by thick curves and thin curves, respectively. The solid curves are for the ratio of thermal spread of energy to the averaged energy $\langle K_{\rm T}\rangle = 9.6\%$, which is near the condition of the present experiment. The dotted curves are for $\langle K_{\rm T}\rangle = 4.8\%$, which is the fusion oriented condition. The open diamonds are for 2-D numerical calculations$^{3)}$ under the fusion oriented condition.

According to 1-D numerical calculations, using varied v_ϕ design, η_1 is relatively kept constant, although it declines for fixed v_ϕ condition. On $L_{\rm D} \sim L_{\rm DM}$ of the fusion oriented condition, 1-D calculation roughly agree with 2-D calculation.

Comparing experimental results with 1-D calculation, the dependence on $L_{\rm D}$ roughly agrees with each other. The slight gap of the absolute values might be caused by insufficient modulation$^{4)}$ of the experiments. The optimization technique of phase velocity of traveling wave was confirmed to be effective.

Reference
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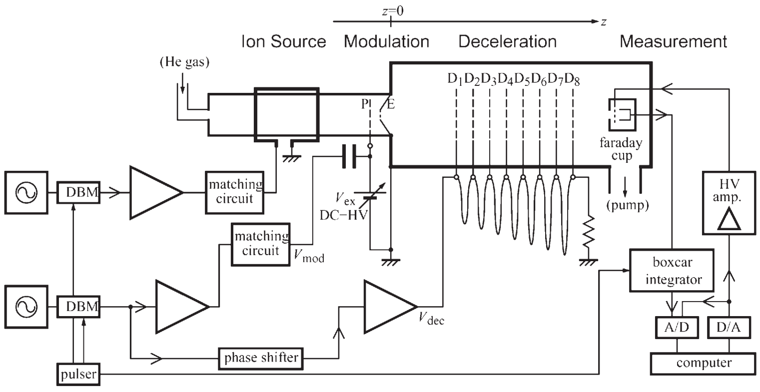

Fig. 1 Experimental setup of the TWDEC simulator.

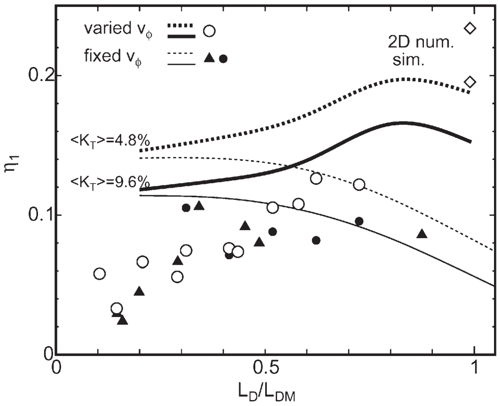

Fig. 2 Scaling of energy recovery.