## §27. Numerical Study of Direct Energy Converters for a Deuterium − Helium FRC Fusion Reactor

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The major portion of produced energy in D-$^3$He fusion plasma will be released as the kinetic energy of charged particles. Two schemes of direct energy conversion have, therefore, been proposed by H. Momota. One is a cusp type converter, which will separate electrons and fusion proton ions and also converts the kinetic energy of electrons and low energy thermal ions, and another one is the traveling wave direct energy converter (TWDEC), which converts the kinetic energy of fusion proton ions into high frequency AC electric power. Results of the TWDEC alone are summarized in this report. The authors have proposed a general analytical scheme and also new cylindrical grids, which are incorporated into two-dimensional analyses. All analyses are carried out for the ARTEMIS reactor.

Basic Equations and Numerical Scheme:
(1) One-Dimensional Analyses: The momentum conservation equation is solved for the proton ions, the electric field with the effect of space charge is estimated by Poisson's equation, and the external electric circuits which can induce the traveling wave are simultaneously solved. (2) Two-Dimensional Analyses: The external electric circuits are not included and voltages of grids are given independently, which play a roll of the boundary condition of Poisson's equation. The r-z plane is divided by triangles and the momentum equation is solved analytically within triangles, whereas Poisson's equation is solved with the Galerkin FEM with the first order triangle elements. The effect of magnetic field is included in the two-dimensional analysis.

Basic Configuration:
The basic configuration of TWDEC is a cylinder with a radius of 5 m and consists of a modulator and a decelerator. The inlet velocity of fusion proton ions is estimated with its kinetic energy of 15 MeV, while the total energy input into the TWDEC is 272.5 MW. After a preliminary optimization, the following parameters are decided:

| | |
|---|---|
| Total length of TWDEC | = 30 m, |
| Wave length of modulator | = $2\pi$ m, |
| Number of modulator grids | = 5, |
| Number of decelerator grids | = 25, |
| Length of modulator | = $2\pi$ m, |
| Length of decelerator | = $2.8\times2\pi$ m, |
| Frequency of travelling wave | = 8.54 MHz. |

Distances of grids are decided to have the maximum interaction between fusion proton ions and travelling wave moving through grids.

Formation of Autonomous Oscillation of Travelling Wave:
(One-dimensional Analysis) An external circuit has been designed for the travelling wave, resulting in autonomous oscillation of travelling wave. Over 70 % of conversion efficiency has been obtained with grid voltage of 1 MV. Then, Fourier analyses have been carried out to find the reason why the distance between the last grid of modulator and the first grid of decelerator of 3.5 $\lambda$ gives the maximum conversion efficiency.

| Position | $I_1$ | harmonics | Ratio | Efficiency(%) |
|---|---|---|---|---|
| 2.0 | 1.11 | 2.32 | 2.10 | 59.2 |
| 2.5 | 1.19 | 1.89 | 1.59 | 65.3 |
| 3.0 | 1.21 | 1.55 | 1.28 | 67.4 |
| 3.5 | 1.17 | 1.35 | 1.15 | 70.9 |
| 4.0 | 1.08 | 1.25 | 1.16 | 68.8 |
| 4.5 | 0.93 | 1.12 | 1.21 | 60.3 |
| 5.0 | 0.73 | 1.19 | 1.62 | 50.0 |

where "Position" stands for the relative position of the first grid of decelerator divided by $\lambda$, $I_1$ the ratio of fundamental wave component to the direct-current component. As can be seen, the fundamental wave and higher harmonics has large effects and thus "Ratio" can play as an indicator of design.

Two-Dimensional Effects: The efficiency and the grid voltage result in 65.5 % and 1.7 MV when the collision loss with the grids is not included, whereas 54.7 % and 1.4 MV are obtained when the collision loss is taken into account. The new cylindrical grid is made of five co-axial, cooling-water circular pipes of one cm diameter. The ratio of open space for protons is 99.2 %. It can be seen that the effect of grids is small in the first half of channel but increases dramatically in the last quarter as the energy of protons is converted into the electric energy. It should be noticed that the proposed system includes total 32 grids and thus the simplest estimation of the conversion efficiency is $0.709\times0.992^{32} = 0.548$. The two-dimensional result of efficiency of 54.7 % is, therefore, very good, although the two-dimensional effects look like rather large from the view point of ion trajectory and potential distribution.