PIC Simulation in the Reversed Magnetic Field of MW-DC Cyclotron Wave Converter

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Abstract: *To develop the vacuum-type microwave DC converter for high frequency, in a region of the whole converter where the z-axial magnetic field was reserved, the motion and z-axial velocity of the electron were simulated. The results showed that the increment of z-axial velocity in the region was* 3.8×10^7 *m/s. Moreover, conversion efficiency in conversion region that is the kinetic energy transfer from transverse direction to z-axial one was 94%.*

Keywords: microwaves; cyclotron wave converter; WPT; RF-DC efficiency.

Introduction

In the wireless power transfer using solid state rectifying antennas, there have been great interests in developing high gain and high RF-DC efficiency. At the microwave band, since diodes that have low-switching loss are developed, the RF-DC conversion efficiency are generally 80-90% and output power from a rectenna is high. On the other hand, at millimeter wave, RF-DC efficiency is lower than 70% and above 90GHz, the efficiency is only a few percent.

Cyclotron wave converter: The device is more appropriate for high frequency. It can convert microwave energy to DC energy with high power and high efficiency. The model of it is shown in Fig.1. The device consists of the following three parts; cavity, conversion region and collector. The input microwave at angular frequency ω_0 induces the transverse electric field in the cavity gap. The cavity is inserted into the constant z-axial magnetic field. Electron beam from the pierce-type electron gun is accelerated in the z-axial direction by the acceleration voltage U_0 and is injected into the cavity. Electron cyclotron resonance is caused inside the resonator and the microwave energy is converted into rotational kinetic energy of the electron beam. In the conversion region, axial magnetic field weakens along the z-axis and rotational kinetic energy of electrons is converted into the z-axial kinetic energy. Finally, the accelerated electrons are collected in the depressed collector, z-axial kinetic energy is converted to electric potential at DC load resistance. The overall RF-DC efficiency η_{tot} is expressed by the product of the efficiencies of each region [1].

$$\eta_{tot} = \eta_{cav} \cdot \eta_{con} \cdot \eta_{coll}$$

η_{cav} is the efficiency of microwave energy transfer from external generator source into rotational kinetic energy of the electron beam in the cavity.
η_{con} is the efficiency of energy conversion from rotational kinetic energy into z-axial one in the conversion region.
η_{coll} is the electron collection efficiency.

Objective: The cyclotron wave converter can be input several tens of kW and is concerned to be capable of having high RF-DC efficiency even at high frequency. Previous studies about the cyclotron wave converter are aimed to output high power at 2.45GHz, and no works at the millimeter wave has performed. Therefore, our objective is to develop the cyclotron wave converter having high efficiency at millimeter wave. In order to achieve high efficiency, it is important to analyze how the high magnetic field affects the velocity dispersion of the electron beam in the conversion region. Addition to that, the magnetic field distribution that is effective in the uniform acceleration of the electrons. For the first step, we start from basic theory of the motion of electrons in the conversion region at 2.45GHz.

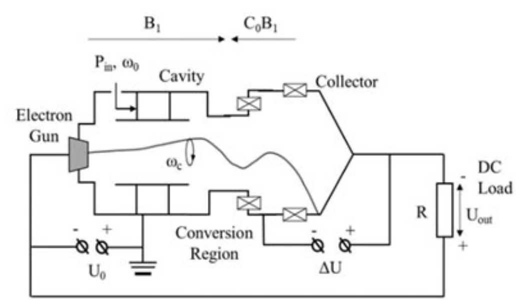

Figure 1. Overview if the cyclotron wave converter.

The Cavity

Cuccia cavity is the simple parallel-plate resonator used for the cyclotron wave converter. By inserting the microwave into the cavity, the transverse electric field $E_1 e^{j\omega_0 t}$ is excited. Initial z-axial velocity of the electrons is calculated by the accelerated voltage U_0. Since no force to accelerate the z-axial velocity, the electrons maintain the z-axial velocity until the end of the region. Moreover, the electrons are affected by the z-axial B field and transverse E field, transverse kinetic energy increases.

PIC Simulation in the Conversion Region

Setup of the simulation: The electron at the center of the beam only in the conversion region (z = 0.0-30.0mm) are calculated by MAGIC3D which is fully electromagnetic 3D Particle-In-Cell simulation. Initial conditions at the entrance of the conversion region are $v_{z0}=2.3\times10^7$ m/s and $v_{trans}=5.9\times10^7$ m/s, respectively [2]. Due to the microwave frequency is 2.45GHz, the initial magnetic field strength is determined at 8.75×10^{-2}T by the cyclotron angular frequency. Considering the situation that the permanent magnet is used to give the magnetic field, the z-axial magnetic field is given as shown in Fig.2. The electric field and time variation of the magnetic field are negligible; thus, the kinetic energy of electrons is preserved, and only spatial distribution of the magnetic field is considered. To satisfy the Gauss's law for the magnetic field, the r component of it is given in the simulation and the magnetic field strength increases as it away from the center.

Results of the simulation: It is confirmed that the radius of the gyration motion is expanding along the z-axis as shown in Fig.3. This is because the rotational velocity is converted to the z-axial velocity. The electrons move along the magnetic force line up to the point, that is B_z=0T, after that, they move away from the line. The result of the z-axial velocity is shown in Fig.4. The z-axial velocity at the end of the conversion region is 6.1×10^7 m/s and the conversion efficiency η_{con} that is defined as the ratio of axial energy increment to the initial rotational energy at the entrance of the conversion region is 94%.

Conclusion

The objective of the study is to develop the cyclotron wave converter for high frequency, since these are few previous works about that. In this paper, the motion of electrons at the center of the electron beam in the conversion region was simulated as the first step. As a result, the increment of z-axial velocity was 94% of the initial transverse kinetic energy at the entrance of the conversion region.

References

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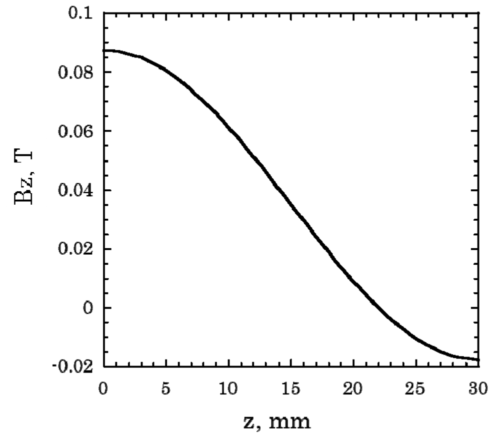

Figure 2. Applied magnetic field in the z-axis direction in the conversion region.

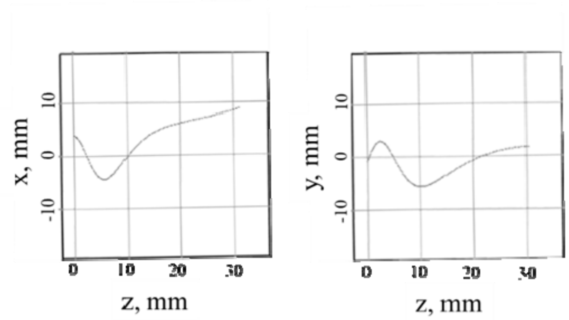

Figure 3. The electron orbit in the conversion region in the x-z plane(left) and y-z plane(right). z=0mm is the entrance and z=30mm is the end of the region.

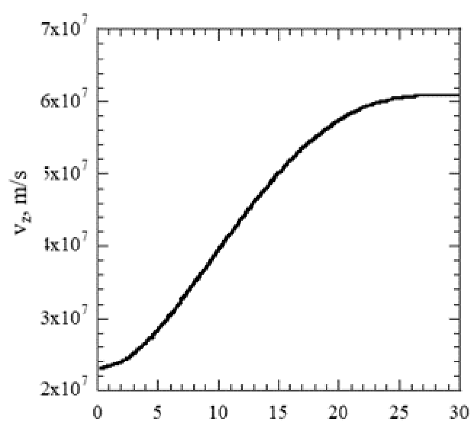

Figure 4. The z-axial velocity along the z coordinate. The maximum value is 6.1×10^7m/s at z=30.0mm.