NONLINEAR ELECTRON ACCELERATION BY CASCADE WAVE TRAPPING FOR VARIOUS HELICON WAVE ANTENNA DESIGNS

V. Petržílka[1], J. A. Tataronis[2], L. Krlín[1] and P. Pavlo[1]

[1]*Institute of Plasma Physics, P.O. Box 17, 182 21 Praha 8, Czech Republic*
[2]*University of Wisconsin, 1500 Engineering Dr., Madison, WI 53706, USA*

1. Introduction

Helicon wave plasma sources are very efficient, and their applications in plasma processing have been very successful. Helicon waves are also used for efficient plasma generation in fusion devices [1]. However, the experimentally established high dissipation of helicon waves still remains a puzzle [2]. It is well known from past experimental studies [2,3] that electrons are accelerated in helicon wave plasmas to energies of tens of eV or even more than $100\,\text{eV}$. Previous theoretical modeling of this effect in terms of *linear* Landau damping, even for a wave with a broad spectrum of phase velocities [4], does not completely explain the experimental data. A real antenna radiates a wave field having a distribution of wave phase velocities. Our numerical simulations of electron acceleration, presented below, imply that the important effect is cascade, stepwise, nonlinear, electron trapping by wave Fourier components with higher and higher phase velocities, as first explored for lower hybrid (LH) waves in [5], and for helicon waves in [6]. This nonlinear approach reveals strongly enhanced electron acceleration and consequently the enhanced wave dissipation. Moreover, the electron acceleration appears to be further enhanced by random electric and magnetic fields arising spontaneously in helicon plasmas. The random fields can be attributed to nonlinear processes such as higher harmonic wave generation, and to wave reflection from the ends of the device. It is noted that harmonic frequencies up to the fifth have been previously measured [7].

2. Theoretical model and computational results

In the computations, we follow the acceleration of an electron ensemble of 1000 electrons, with initial positions equidistantly distributed under the helical and saddle antennae. The injected electrons have randomly distributed initial velocities corresponding to the Maxwell velocity distribution with the temperature of $3\,\text{eV}$. The antennae parameters were chosen as follows: the wire diameter is $0.35\,\text{cm}$, the length is $13\,\text{cm}$, and the length of one turn is $40\,\text{cm}$ for the helical antenna, and it is also the length of the saddle antenna. The antenna is placed in the middle of a linear device of length $125\,\text{cm}$. Plasma edge radius is $2.15\,\text{cm}$, conducting wall radius is $6\,\text{cm}$, and radius of the inner antenna edge is $2.75\,\text{cm}$.

The equation of the electron motion has the following form,

$$\frac{d^2 z}{dt^2} = \frac{e}{m} \left[E_{\text{z}}^{\text{H}}(z,t) + E_{\text{z}}^{\text{ST}}(z,t) \right]. \tag{1}$$

The E_{z}^{H} component of the helicon wave electric field near the antenna, which is parallel to the magnetostatic field, may arise by the following processes:
(i) as a result of finite electron mass in the launched helicon wave, which is the fast wave,
(ii) as a result of excitation of the slow wave, i.e. the Trivelpiece - Gould mode,

(iii) and by the electrostatic coupling of the antenna, which is usually not considered, but which – according to recent experiments – may be very important. It is difficult to estimate correctly all these processes and to give a really good theoretical model of the E_z^{H} field near the antenna. From qualitative considerations, which we made in analogy to the cascade trapping in the LH wave [5], the important factor in the cascade trapping is the wave inhomogeneity with the scale length comparable to the quiver motion amplitude of the electron in the wave, or to the path, which an electron travels in one rf period. Therefore, in the series of computations, which we present here, the space dependence of the helicon wave field E_z^{H} is modeled by using the Fourier transform of the antenna currents. The random fields $E_z^{\mathrm{ST}}(z,t)$ are modeled by wave trains with randomly varying phases [8].

The results are presented in the following **Figures 1 - 5** for a helical antenna, while **Figure 6** considers a saddle antenna:
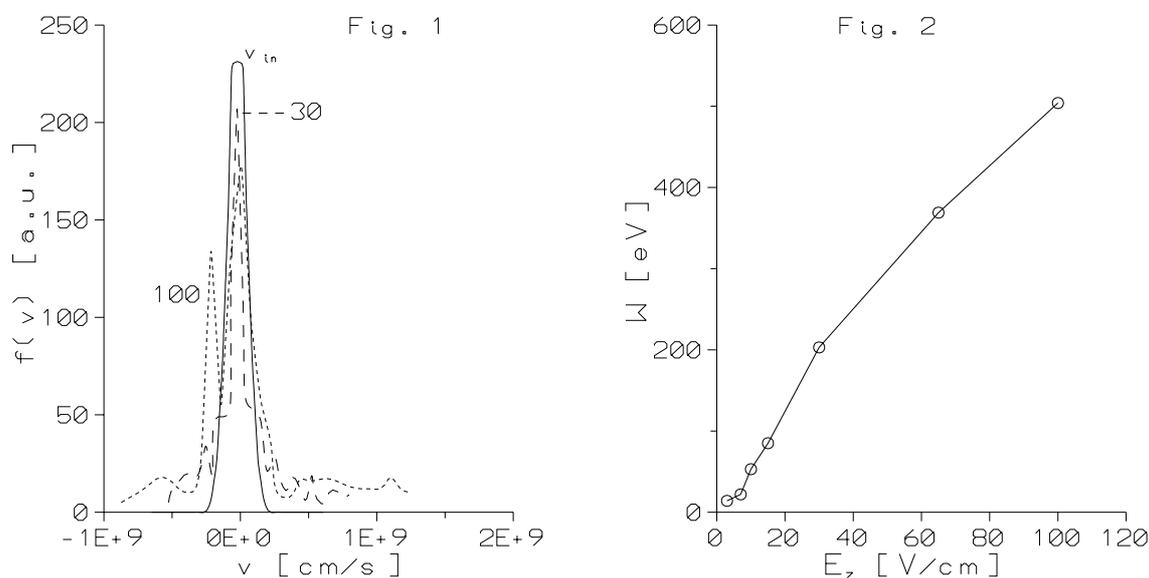

Fig. 1 shows the initial velocity distribution function (solid line), the velocity distribution function of the ensemble of electrons after the acceleration for a very strong helicon wave, with amplitude of E_z^{H} equal to 30 V/cm (long dashes), and the velocity distribution function of the ensemble of electrons after the acceleration for the helicon wave amplitude equal to 100 V/cm (short dashes). The random field amplitude is zero. The helicon wave frequency equals 27.12 MHz. The number of the Fourier components $j = 100$. It can be seen, how the bulk plasma electrons are accelerated to rather high velocities, more than $1. \times 10^9$ cm/s. These velocities correspond to the phase velocity of approximately $j = 10$ component. In **Fig. 2** we see the maximum energy of the most accelerated electron from the electron ensemble, in dependence on the helicon wave amplitude. As in Fig. 1, the helicon wave frequency equals 27.12 MHz, and the number of the Fourier components $j = 100$. **Fig. 3** clearly demonstrates the effect of electron trapping because of the presence of the higher j in the Fourier decomposition. The figure shows the maximum energy of the most accelerated electron from the electron ensemble, in dependence on the the number of the Fourier components j. It can be seen that for $j \geq 5$, electrons with higher velocities from the initial distribution can be accelerated to rather high

temperatures of about 3 keV, what corresponds to electrons moving with the phase velocity of the 2nd or 3rd Fourier component.

Let us analyze the process of cascade electron trapping in more details, using as the example the data of Figure 3: A particle may become trapped by a wave Fourier component j,
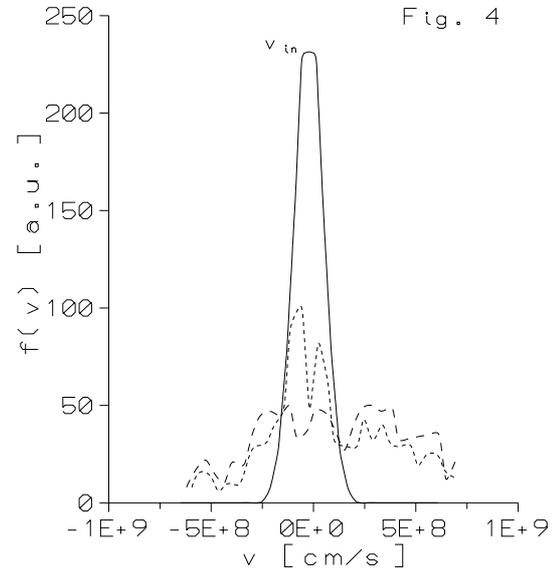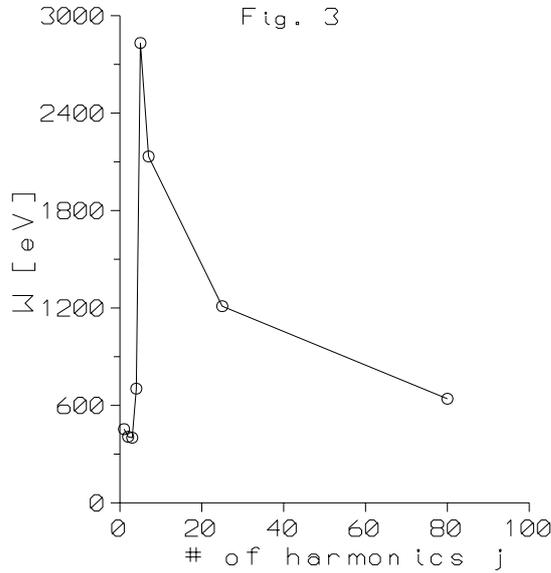

when the sum of its initial velocity v_{in}, of the critical velocity $v_{\mathrm{cr}}^{(j)}$, and of the quiver velocity of the oscillating motion $v_{\mathrm{osc}}^{(j)}$, equals at least the phase velocity $v_{\mathrm{ph}}^{(j)}$ of the j mode. The critical velocity is the velocity, for which the kinetic energy of the particle, in the coordinate system moving with the wave, is larger than the potential well of the wave. For the parameters of Fig. 3, the $j = 5$ is apparently the lowest j, for which the trapping condition, Eq. (12), can be marginally fulfilled. However, there may be in play also an eventual contribution to v_{osc} from other Fourier components. It can be seen that there is a minimum phase velocity v_{min} needed in the spectrum for electron trapping. This is not surprising. However, the high velocity of accelerated electrons, much higher than this minimum phase velocity v_{min}, indicates subsequent cascade wave trapping by wave components with higher phase velocities, as explained for LH waves in [5].

The following **Figure 4** demonstrates the effect of random fields on the electron acceleration by helicon waves. It shows the initial velocity distribution function (solid line), the velocity distribution function of the ensemble of electrons after the acceleration for the helicon wave amplitude equal to 10 V/cm (short dashes), and the velocity distribution function of the ensemble of electrons after the acceleration for the helicon wave amplitude equal to 10 V/cm, and additional random wave field amplitude 1 V/cm (long dashes). The random field frequency equals to the 2nd harmonic frequency of the launched wave. This corresponds to the case, when the random field arises because of the higher harmonics generation [7]. The helicon wave frequency equals 7 MHz. The number of the Fourier components $j = 10$. Even if the random fields do not much enlarge the maximum energy of accelerated electrons, we see that they very significantly enlarge the number of bulk plasma electrons accelerated to high velocities. Just how many electrons are

trapped, depends namely on the number of the Fourier components considered in the Fourier decomposition of the launched field. In experiments, the amplitude of higher j may decrease with the growing radial distance from the antenna, as the high j components with low phase velocity are strongly Landau damped. This implies that the wave may be in reality composed just by a lower number of j.

The last two Figures, **Fig. 5** and **Fig. 6** show the difference between the electron acceleration in the field of the helical and saddle antennae, respectively, for the amplitude of $E_{\mathrm{z}}^{\mathrm{H}}(z,t)$ equal 65 V/cm, frequency 27.12 MHz, but now for $j = 25$.
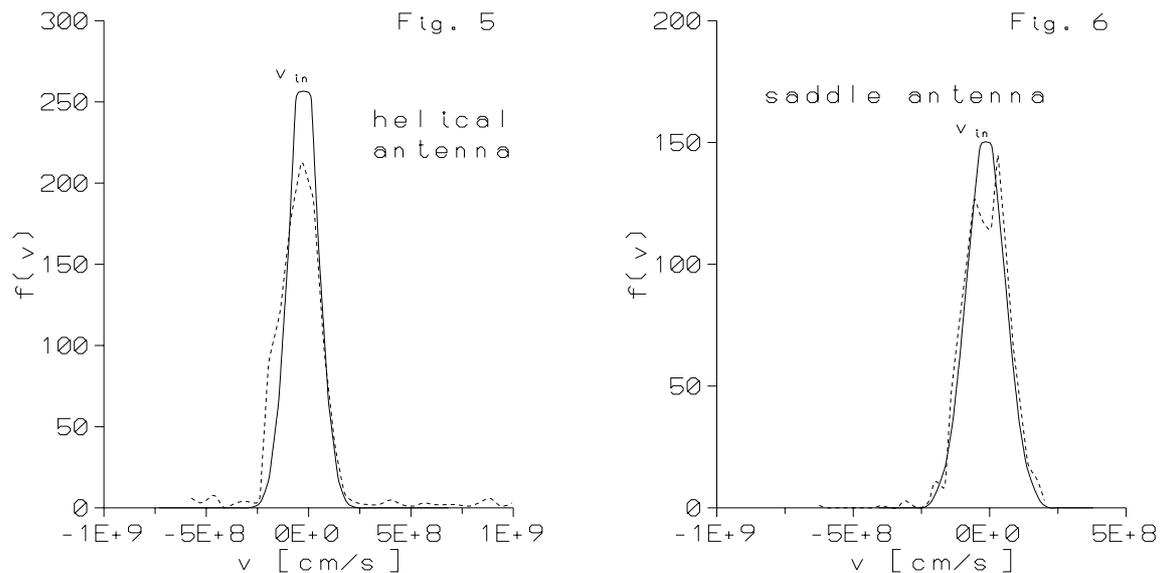
It can be seen that the helical antenna produces significantly larger number of fast electrons than the saddle antenna. Further, the production of fast electrons is more effective for the lower frequency 7 MHz, and – namely for the higher frequency of 27.12 MHz – for higher number of j considered.

Acknowledgment

References

[1] B.D. Blackwell et al.: "H-1 Project." *Int. Stellarator Workshop*, Madrid 1995, p. 26.
[2] F.F. Chen: *in* High Density Plasma Sources, (1995), Chap. 1.
[3] A.W. Molvik, et al.: Phys. Rev. Letters **79**, (1997) 233.
[4] B. Fischer, et al.: Plasma Phys. Controlled Fusion **36**, (1994) 2003.
[5] V. Fuchs, M. Goniche, Y. Demers, et al.: Phys. Plasmas **3**, (1996) 4023.
[6] V. Petržílka and J.A. Tataronis: Bull. Am. Phys. Soc. **42**, (1997) 1930.
[7] R.T.S. Chen, et al.: Plasma Sources Sci. Technol. **4**, (1995) 337.
[8] V. Petržílka, et al.: *2nd RF Heating Conference*, Brussels (1998), p. 149.