The effect of microwave frequency and grad B on the ECR heating

H. Koivisto
Michigan State University, National Superconducting Cyclotron Laboratory, East Lansing, MI 48824-1321, U.S.A

Abstract: In an ECR ion source many parameters are related to the heating of the electrons. The amplitude of the electric field is one of the main factor [1,2]. In addition to this, many other parameters affects the production of the highly charged ions inside the ECR ion source – for example microwave frequency, the strength and configuration of the magnetic field, plasma density, neutral density and so on. Since the ionization becomes more and more difficult when the charge state increases the ionization has to be as efficient as possible. How the gradient of the magnetic field and the microwave frequency will affect the energy of the electron? The computer code to reveal information about these parameters has been developed [3a]. The simulations have shown that more efficient heating will be achieved with higher microwave frequency and with smaller gradient of the magnetic field.

1. Introduction

The energy of electrons used for ionization is increased by the right hand polarized wave. The energy required increases very fast as a function of the charge state of the ion. As a consequence the heating of the electrons has to be efficient. Here, heating means that the energy of the electron is increased by the microwaves. In this paper it is assumed that the energy gain of the electrons can be calculated by using equation $E_e = Ed$, where E is the strength of the electric field and d is the distance the electron is accelerated by the electric field. As a consequence the energy gain increases when the strength of the electric field and/or the distance for the acceleration increases. The strength of the electric field that the electron feels depends on the amplitude and phase of the electron. The distance for the acceleration depends on the time the electron stays in the efficiently accelerating phase, i.e. how fast the phase changes. On the resonance the electron stays at constant phase, i.e. the gyrofrequency of the electron and the frequency of the electric field are exactly same. Equation (1) shows that the gyrofrequency of the electron changes when the mass of the electron m_e or the strength of the external magnetic field B_e changes:

$$\omega = \frac{eB_e}{m_e} \tag{1}$$

In addition to the above mentioned, the phase changes when the electron travels in relation to electromagnetic wave. According to equation $E=E_0\sin\alpha$ the energy of the electrons increases or decreases when they pass the resonance zone depending on their phase with the microwaves.

The heating of electrons has been simulated for example by S. Biri et. al. using so called TrapCad code[3] and by Y. Jongen [4] who suggested that the mirror gradient could affect the temperature of the electrons. In the present work a new computer code was designed in order to calculate the energy gain of an electron when it is heated by the microwaves. The object of these studies was to find out the effect of the gradient of the magnetic field and the microwave frequency on the heating process.

2. Description of the code

Several assumptions were made in order to simplify the problem. It was assumed that in the vicinity of the ECR zone we have a propagating electromagnetic wave and the electrons are heated by the right hand polarized wave. The propagation is parallel to the external magnetic field B_e, i.e. $\overline{B}_e \parallel \overline{k}$. The collisions, electrostatic plasma waves and the plasma potential have been ignored. As a consequence the energy of the electron is changed only by the electric field of the microwave.

The amplitude of the electric field near the resonance region is very difficult to estimate. This issue has been studied for example by M.C.Williamson et. al. [5]. They used Budden tunneling factor [6] on the magnetic beach [7] to find out the absorption of the electromagnetic wave in the resonance region. They found out that the amplitude of the electric field was approximately constant through the resonance region with vanishingly small ε. In that case remarkable tunneling through the singularity occurs. The absorption of the wave increases with the increasing plasma density as a result of which the wave amplitude tends to zero. The wave is absorbed even before it reaches the point where $B=B_{res}$. These results were earlier achieved analytically by T.H.Stix [7].

In this paper two different behaviors for the amplitude were studied. In model_1 it was assumed that the electron is accelerated by the electric field which has a constant amplitude. In model_2 it was assumed that the amplitude of the electric field decreases when the permittivity ε increases according to the dispersion relation for the right hand polarized wave,

$$\varepsilon = 1 - \frac{\omega_p^2}{\omega(\omega - \omega_c)} \qquad (2)$$

where ω_p is the plasma frequency, ω_c is the gyrofrequency of the electron and ω is the microwave frequency. The definition for the permittivity is defined using the cold plasma theory. This breaks down where the velocity of the electron exceeds the phase velocity, i.e. at very close to the resonance. As a consequence, the behavior of the permittivity (and later wavelength) is not so dramatic as is obtained using equation (2). Small amount of damping takes care that refractory index remains finite everywhere. The purpose of comparing these two models was to find out how the different behavior of the amplitude affects the heating process. It was assumed that real behavior of the amplitude of the electric field is between model_1 and model_2. There was no intention to find out the absolute value of the amplitude of the electric field.

In the simulations the heating of the electron was started at the position where $B=B_{res}$. Here $B_{res} = 2\pi f m_e / e$, where f is the microwave frequency and e the elementary charge. The velocity of the electron is divided into the component parallel to the magnetic field and the component perpendicular to the magnetic field. The initial energy of the electron of 1 eV is assumed. This is close to the energy that has been measured for the population of the cold electrons in an ECR ion source [8]. The electron start to travel towards the increasing magnetic field.

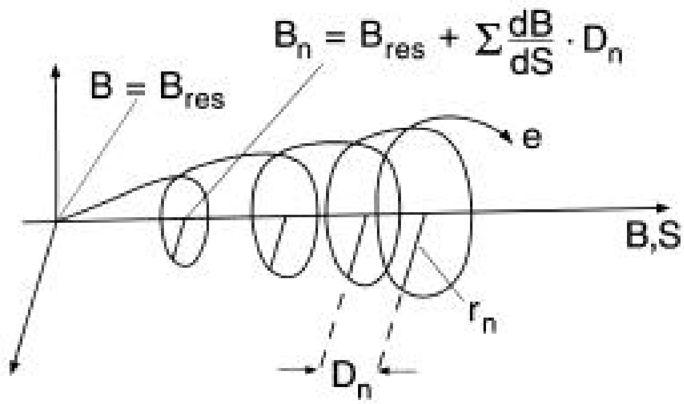

Figure 1: The trajectory of the electron that enters the resonance region from the core of the plasma. The heating of the electron starts at the point where $B=B_{res}$.

Figure 1 shows the trajectory of the electron when it is heated. During the one orbit the energy of the electron is increased by the amount of Ed, where $E = E_0 \sin\alpha$ and $d=2\pi r$. Due to the heating, the radius of the gyro-motion increases. As a consequence the energy gain during one orbit increases. At the same time the guiding center of the electron moves along the magnetic field line by an amount of $D_n=v_n/f$, where v_n is the velocity of the guiding center along the magnetic field line. The strength of the magnetic field increases and the gyrofrequency of the electron changes. As a consequence the phase of the electron with the electric field changes. The phase changes also because the electron moves in relation to the wave. The wavelength was calculated by using equation (3)

$$\lambda = 1/(f\sqrt{\varepsilon\varepsilon_0\mu_0}) \tag{3}$$

According to the (adiabatic) invariance of the magnetic dipole moment the perpendicular velocity of the electron increases with the increasing magnetic field. The magnetic dipole moment μ is not invariant if the energy is changed by using external energy. As a consequence equation (4) has been used to calculate the effect of the heating of the electron on the velocity of its guiding center:

$$F_{\parallel} = -\mu \frac{dB}{dS} \tag{4}$$

where S is the direction along the magnetic field line. The magnetic dipole moment μ increases fast during the heating process. Due to the opposite force, described in equation (6), the parallel velocity decreases and the distance which the guiding center travels during each orbit decreases. If the heating is efficient enough (or B increases enough) the electron is eventually reflected back. The strength of the magnetic field during each orbit of the electron has been calculated using equation (5)

$$B = B_{res} + \frac{dB}{dS} D_n \tag{5}$$

In the calculations the relativistic theory was used. All values were calculated 18 times during one orbit.

3. Simulations with the code

Simulations are based on the magnetic field of the 6.4 GHz RT-ECRIS in the National Superconducting Cyclotron Laboratory at Michigan State University. The normal maximum field (i.e. using normal settings of the solenoids) on the middle axis of the chamber is 0.4 T and 0.3 T, for the injection and extraction end of the ion source, respectively. The total magnetic field on the wall is 0.35-0.6 T. The magnetic field of the source was calculated with the aid of the Poisson code [9] and Permag code [10]. The combination of these codes gives the information involving the direction and gradient of the magnetic field.

The strength of the magnetic field at the resonance point is 0.2287 T, which corresponds to the microwave frequency of 6.4 GHz. The magnetic field for the simulations has been calculated on the plane that goes through the middle axis of the plasma chamber and through one of the hexapole magnets. The starting point for the electron was just inside the ECR zone at this plane and where the distance to the wall of the plasma chamber is smallest. At this point the magnetic field has components B_r and B_z. As a consequence, the electron travels towards the multipole magnet. The gradient of the magnetic field at the starting point is about 1 T/m. The electron can travel about 80 mm before it collides with the wall of the plasma chamber. At that point the gradient is about 4 T/m. The change of the gradient along the magnetic field line has been taken into account.

In the first simulation the frequency and the magnetic field described above were used. Figure 2 shows the change of the energy of the electron during one heating period. Here the heating period means the period when the heating of the electron is started, and it is reflected back and crosses the B_{res} field again. In these calculations model_1 was used. This means that the amplitude of the electric field was constant during the heating process. The original velocity of the electron corresponded to the energy of 1 eV. Four different angles (between the velocity and magnetic field) and phases for the electron was used. The amplitude of the electric field during the heating process was chosen to be 20kV/m. X denotes the position where the electron is reflected back. The curve b corresponds to the heating of the electron when it enters the resonance zone with the optimum angle and phase. The phase is 90 degrees when the velocity of the electron is parallel to the electric field. The curve d corresponds to the simulations where the electron is reflected back and goes to the deceleration phase. Consequently the energy finally falls to zero. In that case the angle between the velocity and the magnetic field line was 2 degrees and the phase with respect to the electric field was 90 degrees. The distance D between the reflection point and the ECR zone along the magnetic field line was as follows: a) D=0.15mm, b) D=1.84mm, c) D=1.40mm and d) D=2.08mm. In this point the reader should recall that the plasma potential has been ignored in the code. This will affect the distance the electron travels before the reflection.

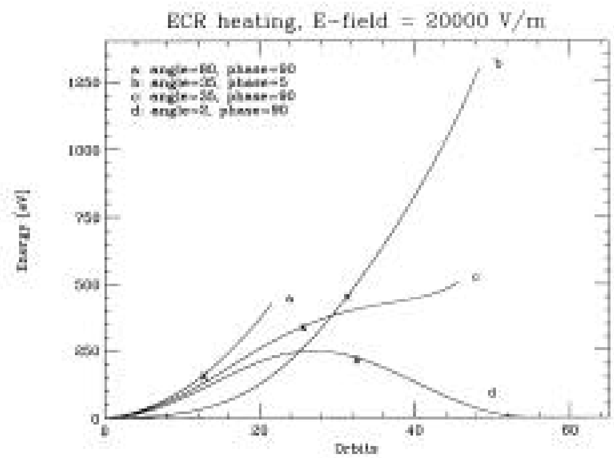

Figure 2: The energy of the electron as a function of the number of the orbits. The turning point of the electron is denoted by x. Four different angles and phases of the electron were used.

The behavior of the electron's energy using model_2 is quite similar to the results shown in figure 2. Only the angle and phase for the maximum heating efficiency are different. The higher power input has to be also used in order to achieve same final energy. This is because the electric field amplitude was allowed to decrease with the increasing permittivity. How the different initial energy of the electron will affect the heating? This has been studied as a next step.

Figure 3 shows the electron's energy as a function of the heating time/orbits. Four different cases are shown. In the case of a) the electron has initially accelerating phase and it's energy is increased. Due to the high original energy the electron travels with the high velocity along the magnetic field line even with the high value of the angle. As a consequence the electron chances it's phase fast respect to the electric field. As figure 3 shows the electron goes to the decelerating phase just before the reflection point. The energy start to decrease and has finally almost the same value as it was before the heating. The electron was reflected back when the guiding center was traveled 4.9mm along the magnetic field line. In the case of b) the electron has higher parallel velocity and it goes to the decelerating phase twice during the heating period. It traveled 8.3 mm before the reflection. In the case of c) the parallel velocity is very small comparing to the perpendicular velocity. As a consequence the electron is easily reflected back after travelling 0.3 mm along the field line. In the case of d) the electron travels along the field line with the high velocity. It goes to the accelerating and decelerating phase several times. The energy oscillates around the initial value and finally the electron collides with the wall. With the optimum angle and phase the energy of 2.8keV was reached.

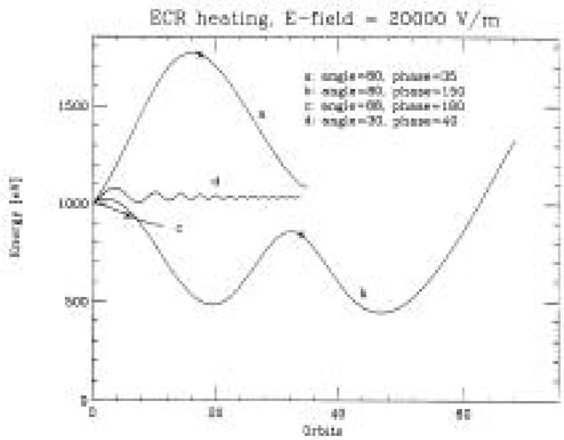

Figure 3: The energy of the electron as a function of the heating orbit numbers. The initial energy of 1 keV was used. The reflection point is denoted by x.

One difference concerning the heating can be found comparing figures 2 and 3. With the small initial energy of the electron the confinement is more critical for the phase of the electron respect to the electric field. With the higher energy the confinement is more critical for the angle of the electron's velocity respect to the direction of the magnetic field.

As a next step the effect of the gradient of the magnetic field and the effect of the microwave frequency were studied. The initial energy of the electron before the heating was chosen to be 1 eV. The electron is heated as long as the requirement $B>B_{res}$ is fulfilled. The final energy corresponds to the optimum situation, i.e. when the electron enters the resonance region with the optimum angle and phase. The optimum was found by varying the angle between the velocity of the electron and the magnetic field line in increments of 1 degree (1-89 degree) and the phase in increments of 5 degrees (5-360 degree). Four different gradient of the magnetic field were studied: 0.5T/m, 1.0 T/m, 2.0 T/m and 4.0 T/m. The microwave frequency varied from 1 to 25 GHz. An electric field amplitude of 20kV/m was used.

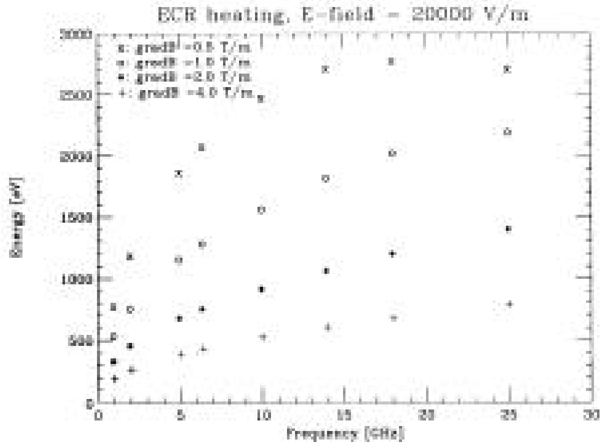

Figure 4: The energy of the electron as a function of the microwave frequency when different gradients of the magnetic field were used. The initial energy of the electron was 1 eV. Points correspond to the maximum energy obtained during one heating period with optimum angle and phase. Constant amplitude of the electric field was used.

Figure 4 shows the results of the simulations. The energy gain of the electron increases when the gradient of the magnetic field decreases or the microwave frequency increases. The behavior is very close to the behavior of $n\sqrt{f}$, where n is a constant. The value of n depends on the gradient of the magnetic field and the amplitude of the electric field. The relativistic effect causes a deviation from this behavior at high energies.

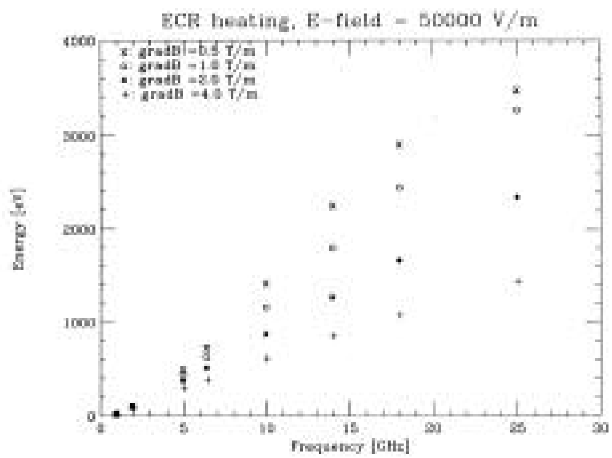

Figure 6: The energy of the electron as a function of the microwave energy when different gradients of the magnetic field were used. An initial electron energy of 1eV was used. Points correspond to the maximum energy obtained during one heating period with optimum angle and phase of the electron. The amplitude of the electric field decreases as a function of the permittivity according to equation (2).

Figure 5 shows the same simulation as in figure 4 except the amplitude of the electric field varies due to the change in permittivity as was described earlier. The efficiency of the heating increases when the microwave frequency increases and when the gradient of the magnetic field decreases, just as before. It increases almost linearly with microwave frequency. The increase of the mass with high energies again causes deviation for this behavior. In these simulations the electric field amplitude of 50kV/m was used.

4. Summary and Discussion

The simulations showed that more efficient heating of the electrons in the ECR ion source is achieved when a higher microwave frequency or smaller gradient of the magnetic field is used. This result is valid regardless of the behavior of the amplitude of the electric field in the vicinity of the resonance region. The energy gain dE_e/dt increases when microwave frequency f increases. With same initial velocity, the distance the electron travels during one gyro-period decreases with increasing microwave frequency. The change of the phase during one orbit decreases and the number of orbits the electron stays in the efficiently heating phase increases. This gives a higher final energy of the electron.

The results obtained here support the use of higher microwave frequencies. Necessarily, the higher frequency is not better if at the same time the gradient of the magnetic field increases vigorously. In ECR ion sources the highest gradient of the magnetic field lies near the wall of the plasma chamber and near the mirror points, i.e. where B_r or/and B_z changes strongly. The most effective heating of the electrons will occur where the magnetic field has its smallest gradient. The smallest gradient lies in the middle of the mirror points and where the magnetic field has only the components B_φ and B_z.

The smaller over-all gradient of the magnetic field at the ECR region is achieved when the distance between the wall of the plasma chamber (and mirror points) and ECR zone is long enough, i.e when the ECR zone lies close to the axis (and far away from mirror points). This supports the use of the so-called high-B mode [11]. The calculations with the POISSON code show that higher current in the coils decreases the gradient of the magnetic field at the ECR zone. According to the results obtained in this paper, the magnetic field should be designed so that the as low gradient of the magnetic field as possible lies in the heating region. This improves the heating of the electrons. Outside of this heating region the magnetic field should increase as fast as possible in order to improve the confinement of the ions and the electrons that have collided with neutrals or ions and are moving towards the wall of the plasma chamber.

Acknowledgement

The support and comments received by Prof. R. Geller, Dr. T. Grimm and Dr. P. Miller are gratefully acknowledged.

[1] R.Geller, Proceedings of the 11th International Workshop on Electron Cyclotron Resonance Ion Sources, May 6-7, Groningen, (1993), p.1.

[2] R.Geller and B. Jacquot, Phys. Scripta T3, (1983), p.19.

[3a] H. Koivisto

[3] S.Biri, A. Valek, J. Vamosi, Proceedings Of the 12th int. Workshop on ECR ion sources, April 25-27, RIKEN, Japan, (1995), p.207.
[4] Y.Jongen, Proceedings of the 6th Workshop on ECRIS, (1985), p. 238.
[5] M.C.Williamson, A.J.Lichtenberg, and M.A.Lieberman, J.Appl.Phys., 72(9), 1 November, (1992), p.3924.
[6] K.G.Budden, Radio Waves in the Ionosphere, Cambridge University Press, (1961).
[7] T.H.Stix, The Theory of Plasma Waves, McGraw-Hill, New York, (1962).
[8] K.S. Golovanivsky and G. Melin, Rev. Sci. Instrum. 63 (4), April (1992), p.2886.
[9] Los Alamos Accelerator Code Group, Reference manual for the Poisson/ Superfish group of codes, Los Alamos National Laboratory, January 1, 1987.
[10] Z.Q.Xie and T.A.Antaya, The Permag Code, National Superconducting Cyclotron Laboratory, September 1987.
[11] T.A.Antaya and S.Gammino, Rev. Sci. Instrum., 65 (5), May, (1994), p. 1723.