Manuscript for trapping analysis

**Abstract**

A math model is presented to illustrate the trapping effect of electrons in a static electric field by an electromagnetic wave through anomalous Doppler resonance under a uniform background magnetic field. When the electromagnetic wave intensity surpasses a threshold, the electron’s parallel velocity becomes trapped and oscillates within a pseudo-potential well. In this trapping region, energy from the static electric field is continuously converted into gyrokinetic energy. The energy transfer ratio from the static electric field to the gyrokinetic is calculated and compared with predictions from quantum theory, showing good agreement.

**I Introduction**

The manipulation of particles via electromagnetic (EM) waves is a powerful and versatile technique, primarily employed for two key objectives: particle acceleration and trapping. In the context of acceleration, one prominent mechanism is autoresonance, wherein a charged particle sustains phase synchronization with an EM wave through nonlinear effects. A well-known example is the Gyro-Resonant Accelerator (Gyrac), in which electrons resonate within a time-varying magnetic field while interacting with a fixed-frequency EM wave (see The Gyrac: A Proposed Gyro-Resonant Accelerator of Electrons), the smooth augmentation of the magnetic field is automatically accompanied by a correspondent growth of the relativistic electron mass. Additional acceleration mechanisms include betatron resonance (Particle Acceleration in Relativistic Laser Channels) and ponderomotive-force-driven acceleration (Laser Electron Accelerator, T. Tajima).

For particle trapping, spatial confinement can be achieved using methods such as optical tweezers or ponderomotive potential wells generated by the spatial interference patterns of laser beats (High-Efficiency Nonadiabatic Trapping of Electrons in the Ponderomotive Potential Wells of Laser Beats). Velocity-selective trapping, on the other hand, can be realized through Landau resonant, wherein electrons with velocities near the phase velocity of a longitudinal wave become confined within the associated potential well.

Although the interaction between test particles and EM waves has been extensively examined, few studies have incorporated the role of a static electric field in such interactions, despite its relevance in phenomena such as runaway electron generation in tokamaks. Building upon analytical approaches used to study electron pitch-angle scattering in EM waves (e.g., Paper1), we extend existing models by introducing a static electric field, thereby uncovering a previously unexplored form of resonant trapping in EM wave–particle interactions. In this study, we numerically investigate a novel trapping phenomenon in which electrons within a static electric field become confined at the anomalous Doppler resonant velocity under the influence of a left-hand circularly polarized plane EM wave in a uniform magnetic field. Under these conditions, the work performed by the static electric field is continuously converted into gyrokinetic energy, thereby sustaining resonance with the EM wave.

The paper is organized as follows: In Section II, we present a mathematical analysis of the interaction between an electromagnetic wave and an electron in the presence of a static electric field aligned with a uniform background magnetic field. Section III provides a numerical investigation of the resulting trapping phenomenon. In Section IV, we analyze the physical mechanism and derive the critical threshold conditions required for trapping. Finally, Section V offers a discussion of the results and a summary of the main conclusions.

**II electron-electromagnetic wave interaction analysis**

**2.1 Field equations**

To analyze interaction under the anomalous Doppler resonant, we consider an electromagnetic wave with left-hand circular polarization (LCP) whose phase velocity satisfies < c, where ω is the angular frequency and k is the wavenumber. The wavevector k is aligned parallel to the uniform background magnetic field B₀ = B₀ẑ. The wave's magnetic field perturbation B̃ is characterized by the dimensionless parameter κ ≡ |B̃|/B₀, such that the total magnetic field becomes **B** = B₀ẑ + B̃. The system includes a static electric field E₀ = E₀ẑ, with the total electric field given by **E** = E₀ẑ + Ẽ, where Ẽ represents the LCP wave electric field components:

Here, is the wave electric field amplitude, and the polarization satisfies the LCP condition for electron cyclotron interactions in the anomalous Doppler regime.

Faraday’s law requires the associated magnetic field to be

Here .

**2.2 Transformation to the wave frame**

In wave frame, which denotes as prime and moves at constant velocity with respect to the lab frame, the fields are

Where . Substituting the wave fields Eq. , Eq. into Eq., Eq. gives and .

Since and {**x**, ict} are relativistic four-vectors, we have

here is the wavenumber in the wave frame. The wave magnetic field is than

the motion equation of the charge particle in the prime frame is

Where , m is the rest mass of electron. Note that ,, and differ and should not be confused with each other. The derivation of energy to t’ should be equal to

Here is the nonrelativistic electron cyclotron frequency in the lab frame with , according to Eq. , Eq. , we have

Combining with Eq. , we obtain

Where

**2.3 Construction of pseudo-potential problem**

Taking the derivative of Eq. with respect to t’ gives

Here we ignore the derivative of as , the time derivation of wave magnetic field in wave frame is

where .Substitution using Eq. ,Eq. and Eq. into Eq. gives

Ignoring the high order of terms gives

here . Introduce the

The parameter ξ characterizes the frequency mismatch relative to the anomalous doppler resonance condition given by

This relationship can be derived as follows. Starting from the definition of σ, we have:

Since {} are four-vector, we have Substituting Eq. and Eq. into Eq. gives

The actually is nonlinear function of , which is different with no static electric field as in paper  [1],since

To express approximately linearly with , the following condition must be satisfied:

This leads to the requirement:

Since ,we have

Thus, the condition for linearity reduces to . For instance, when we find , which satisfies the inequality. Therefore, in the regime where , the dependence of on can be considered approximately linear.

**2.4 connect with**

To obtain the relationship between and , inserting Eq. and Eq. into the time derivation of gives

where

and

Finally, we have

The equation is first-order linear differential equation with the form:

The solution of z is

here and , . Since P << 1, we have

Ignoring the second term of the Eq. , the expression can be written as:

The substitution of Eq. into Eq. gives

Integrating Eq. with and ignoring the second term on the right sight gives:

Noting that t = 0 corresponds to z’=0, since z = 0 at t= 0, and recalling the four vectors {}, we have the relation:

Since is in the y direction when z’ = 0, it follows that

Where is defined by and , . With these definitions, Eq. becomes

The substitution of Eq. into Eq. gives

Simplifying Eq. and substituting for gives:

Since and , we can safely abandon the last term and then Eq. written as

The Eq. could also be written as

Where

Multiplying Eq. by and integrating gives a pseudo-energy equation

Where

And

Here ,, The pseudo potential can only be solved numerically, as it does not have a regular form involving only the parameter , here also depends on t’ , which is related to and .

**2.5 Initial condition**

From Eq. and , we see that

At the start where t = 0 and z = 0, we have

Ignoring the higher order of , we have

**2.6 Solve**

According to Eq., multiplying on both sides gives

Ignoring third term on the right side and reorganize the equation, we have

According to Eq. , multiplying on both sides gives

Add Eq. and Eq. , we have

Which means energy change ratio equal to work done by static electric field in moving frame.

Integrating both side with t’ gives

**III. Numerical study of the trapping effect**

According to Eq. and Eq., the velocity could be numerically solved by ode45, and subsequently, can be determined from Eq. . Then, using the four-vector {}, we have:

Based on the resonance condition given in Eq. , the resonant velocity is given by , where . To ensure that the resonant velocity remains within the linear regime of , the condition must be satisfied, as required by Eq. , it follows that the refractive index must fulfill the inequality

In case I, Fig. 1 illustrates an example of an untrapping scenario with Ew=40 V/m. For the static electric field E0 < 0, the direction of the electric field is opposite to that of the background magnetic field. As a result, the parallel velocity increases over time, as shown in Fig.1(a). Since here because of , the value of decreases as increase according to Eq. . When the parallel velocity satisfies the anomalous doppler resonance condition where , the perpendicular velocity increase abruptly, as shown in fig.1 (b-d), After the parallel velocity exceeds the resonance condition, the will no longer increase. The phase evolution of and is shown in fig.(e). It can be observed that the fluctuation of is stronger for than for . This is because the increase of and is proportional to as shown in Eq. . Fig.(f) illustrates the pseudo-potential , defined as .The initial pseudo-kinetic energy . Although the pseudo-potential increases after the resonance point (ξ<0), the initial pseudo-kinetic energy remains greater than the pseudo-potential throughout, indicating that no trapping occurs.

In case II, the electric field of the electromagnetic wave is increased to 40 V/m. As the electron’s parallel velocity approaches the resonant velocity, it no longer increases continuously but begins to oscillate around the resonant velocity, as shown in Fig. 2(a). While on the other hand, the perpendicular velocity increases continuously when trapping in resonant region, as shown in Fig. 2(b-d). The phase trajectory of ( is shown in Fig.2 (e). The closed-loop structure indicates periodic motion around the resonant point, and the direction of motion is labeled with arrow. The electron can only propagate within the region where the pseudo-potential is lower than the initial pseudo-kinetic energy E0. When the pseudo-potential tends to suppress the E0, the electron velocity rebounds upon reaching the boundary of the pseudo-potential well. Consequently, the electron becomes confined within the well, the width of the pseudo-potential well also increases, since it is influenced by the parameter . This bounce effect, shown in Fig. (f), illustrates the trapping phenomenon.

Since the pseudo-potential Δψ(ξ) depends on ​, we introduce a new coordinate defined as ​, and relabel ξ as ​ to emphasize its association with the parallel direction. This transformation enables clearer visualization of the pseudo-potential structure in the (ξz​,ξ⊥​) plane. An example is shown in Fig. 3, which compares the two scenarios described in Case I and Case II. It can be seen that when the electron becomes trapped under the resonant condition, it slips into a “deep potential valley” that extends further along the direction. In contrast, if the electron passes through the resonant region without being trapped, it continues on a “highway”-like trajectory without further obstruction.

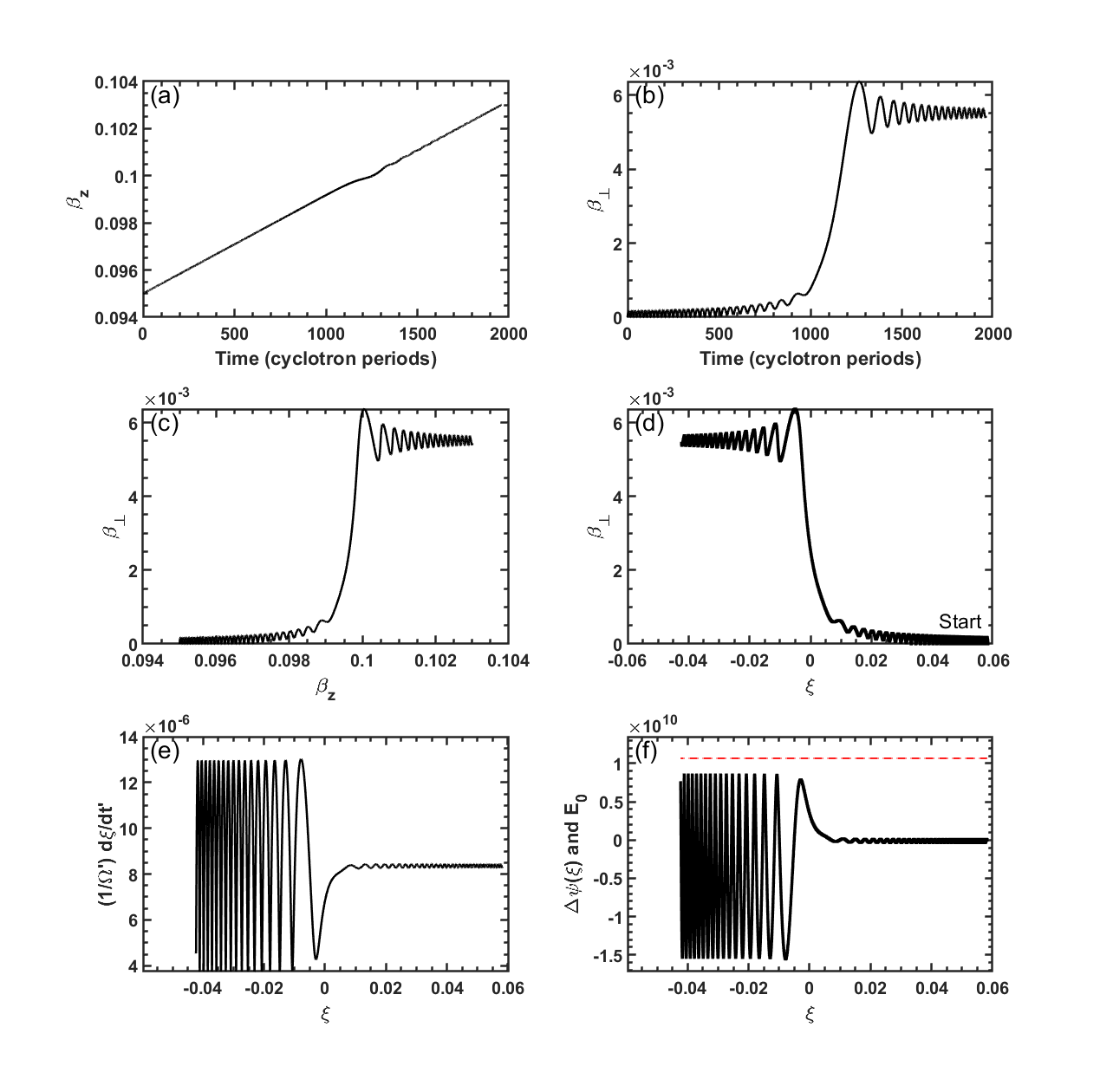


Figure . Numerical integration of Eq. with initial equation Eq. . Input parameters are E0 =- 20 V/m, Ew = 40 V/m, B0 = 0.1 T, , initial pitch angle =0, initial , 0, n = 50. This give (a) The time evolution of . (b) The time evolution of .(c)The velocity phase in ( , . (d)The evolution of with . (e) The evolution of with ξ. (f)The pseudo-potential (black line)and the initial pseudo-kinetic energy E0 (red dash line)

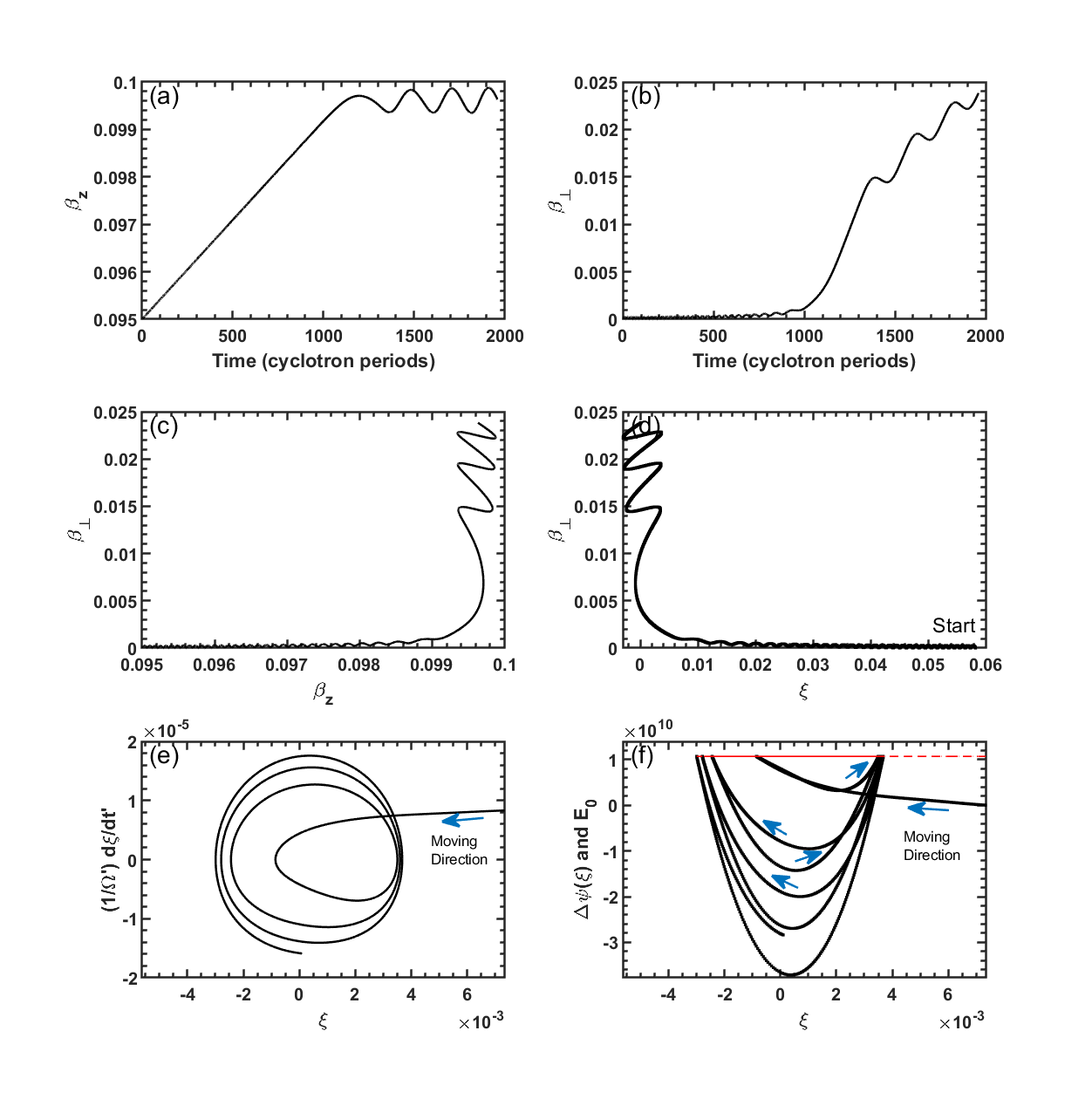


Figure . Same as Fig. (1) except with Ew=60V/m. This gives but same . Panels (e) and (f) show a zoomed-in view around .

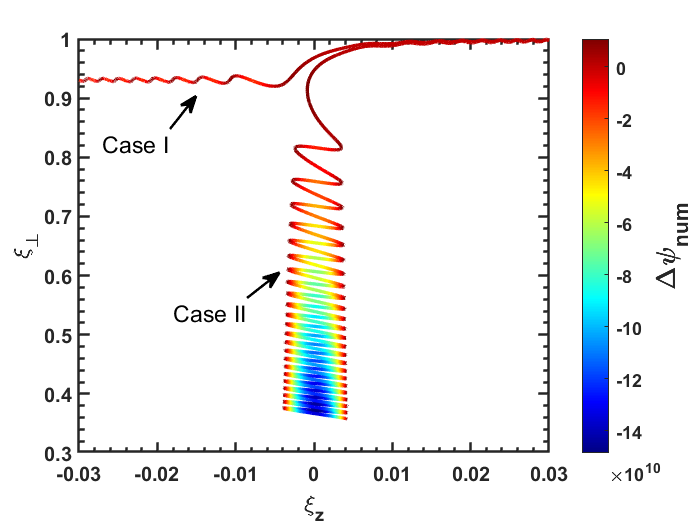


Figure . Pseudo-potential Δψ mapped along the electron trajectory in the () plane.

To determine the critical boundary of the trapping region, according to Eq. and Eq., if we consider the initial perpendicular velocity to be approximately zero ( ), then s =0 and the equations is governed only by two coefficients: and .It is possible to find the boundary by scanning the parameters of and . As shown in Fig. 4, the trapping region is indicated in yellow, while the blue region corresponds to the passing regime. Case I and Case II are marked with star symbols in the figure, located in the passing and trapping regions, respectively. Since we only consider the situation where , we can approximate , then . Under this assumption, one can readily determine whether the electron will be trapped by calculating and and identifying the corresponding location on the parameter map.

**Benchmark with quantum theory**

One characteristic worth pointing out is that when the electron is trapped in the electromagnetic wave, the energy transfer from the static electric field to the gyrokinetic energy is governed by quantum theory (QE theory) (ref2)

Here n = 1, and for anomalous Doppler resonance, ,Therefore, can be written as

For we have 0.8. To numerically calculate the energy transfer ratio, we evaluate the work done by the static electric field during resonance:

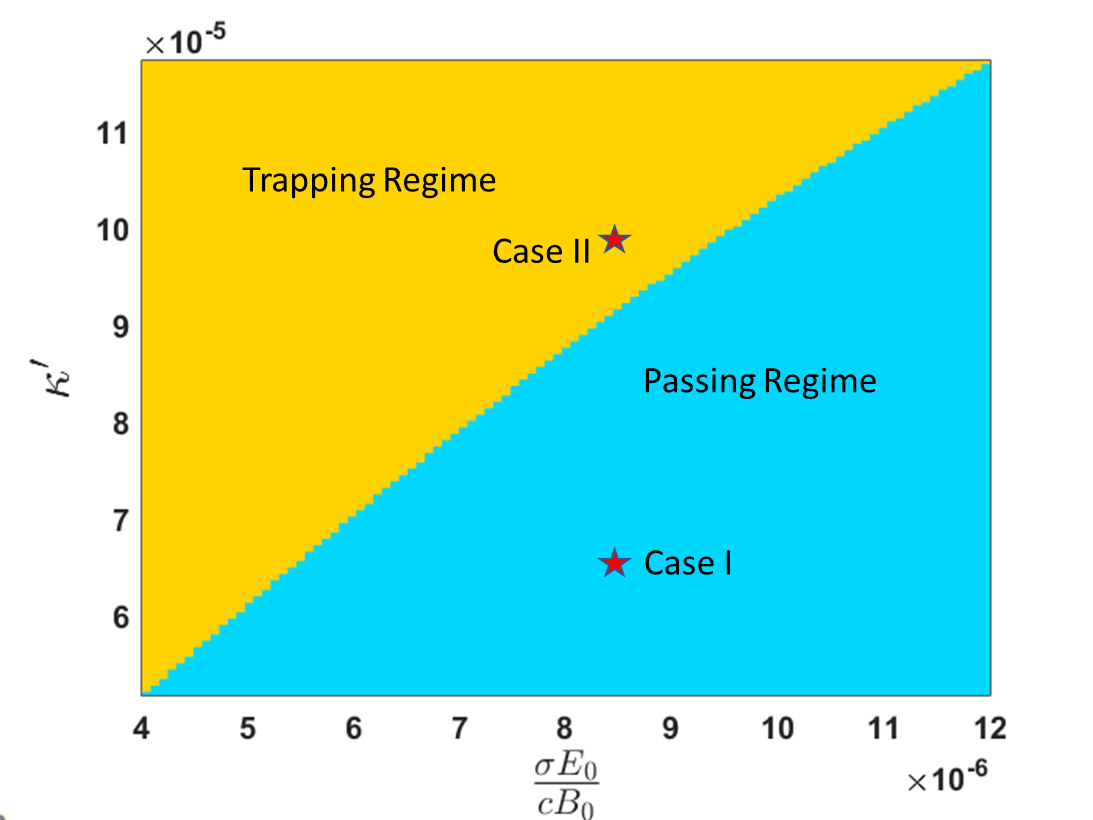


Figure . Parameter space of () showing electron trapping (yellow) and passing (blue) regimes. Here the initial condition is set to and the simulation time spans the interval [0 4960] cyclotron periods, which could ensure the electron has sufficient time to interact with the resonant region.

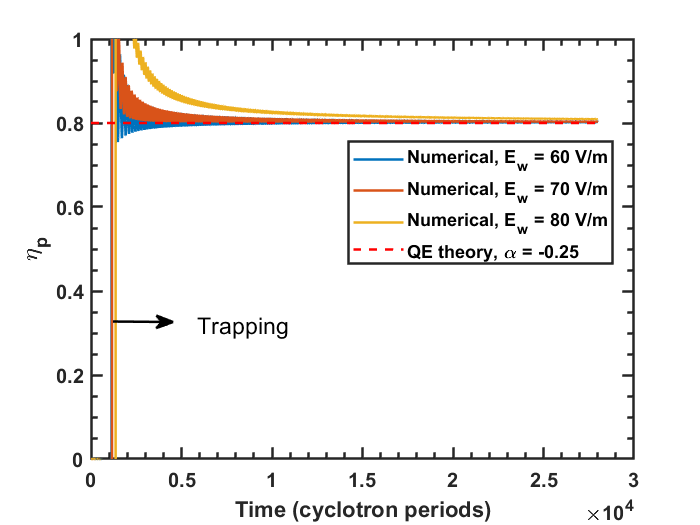


Figure . Energy transfer ratio from the static electric field to the gyrokinetic energy. The parameters used here are the same as in Figure 2 except Ew. QE theory means theory based on quantum equation.

Here refers to the beginning of trapping time. The increase of perpendicular energy is given by

Finally, the energy transfer ratio is calculated as .

The ηₚ values obtained from the two methods are illustrated in Fig. 5. As electron is trapped by electromagnetic wave, the energy transfer ratio from the numerical results tends to approach the theoretical prediction, and this ratio is independent of the wave’s intensity. The agreement between the numerical and theoretical results confirms both the accuracy of the simulation and the consistency between quantum theory and classical dynamics.

**Discussion**

This trapping effect can also be qualitatively understood through the conservation of angular momentum and linear momentum. We can draw an analogy by treating the cyclotron electron as a system that contains both internal and kinetic energy — where the internal energy refers to the gyrokinetic energy and the kinetic energy refers to its translational motion along the magnetic field. When this system is stimulated by an external left-hand polarized electromagnetic wave, it undergoes stimulated emission, radiating a wave identical to the external one.

Since the emitted wave travels in the same direction as the system, conservation of linear momentum requires the system to lose some of its parallel momentum. Simultaneously, because the electron possesses right-hand polarization (associated with positive angular momentum), while the emitted wave has left-hand polarization (associated with negative angular momentum), the system must gain angular momentum to conserve total angular momentum between the electron system and the emitted photons.

As a result, the system loses kinetic energy and gains gyrokinetic energy. However, a static electric field continues to replenish the lost kinetic energy. When the rate of energy loss to the wave balances the energy input from the electric field, the electron's parallel velocity ceases to increase, and the electron becomes trapped in the electromagnetic wave. This manifests as a continuous transfer of energy from the static electric field to the gyrokinetic energy of the system.

**Summary**

In conclusion, we illustrate that during electron trapping, the parallel velocity behaves like an oscillation in a potential well, while the perpendicular velocity continuously increases. The parameter boundary of the trapping region is given by the condition . In the low refractive index region, this trapping effect is also expected to occur but is beyond the scope of this paper, as the linear relationship between ξ and βz ​ breaks down under resonant conditions. The energy conservation ratio between the numerical simulation and quantum theory is also provided, showing strong agreement.

This trapping phenomenon might have multiple applications like electron acceleration, wave generation, and so on. The simple model may be worth more consideration in runaway suppression in tokamak, as the high energy would cause severe damage to the device, and the idea that by suppressing runaway electron energy through anomalous resonance is an attractive method. Furthermore, in magnetic mirror plasma devices, electrons escape through the loss cone, which is defined by the relation , Electrons possessing parallel velocities exceeding ​ are lost from the confinement region. If we inject electromagnetic wave from both end side of the magnetic mirror to trapping the velocity below may provide an effective mechanism for reducing particle losses.