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A PROPOSED EXPLANATION OF HIGH-MINIMUM-B INSTABILITIES

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Abstract

It is well-known that electron cyclotron resonance ion sources exhibit instabilities when these sources' minimum magnetic fields are approximately 80% of the resonant field or greater, but the reasons for this instability have yet to be satisfactorily explained. We show that raising the minimum field makes much faster heating modes accessible at lower energies that invite the onset of kinetic instabilities.

KINETIC INSTABILITIES

Electron cyclotron resonance ion sources (ECR ion sources or ECRISs) are an effective means of producing high current, highly-charged ion beams [1,2]. These sources typically rely on a superposition of solenoidal and sextupolar magnetic fields to confine a plasma via magnetic mirroring. Electrons are heated resonantly by injected microwaves near closed surfaces of constant magnetic field that surround the source's minimum magnetic field center. Decades of experience with these sources has shown high-charge-state production is optimized when the axial fields have maxima of approximately twice the resonant field at the beam-extracting end of the source and three-to-four times the resonant field at the opposite end, while maintaining radial fields that are approximately twice the resonant field on the plasma chamber surface. The central field is typically set so that its minimum is in the range of 50-to-80 percent of the resonant field. It has been found for all ECR ion sources that as the minimum field is increased to, and especially beyond, 80 percent of the resonant field the confined plasma becomes increasingly unstable. When this happens, the plasma expels strong bursts of high-energy electrons that have been associated with kinetic instabilities arising when the electron energy distribution increases with energy [3].

Kinetic instabilities can develop in systems where particles gain energy much more quickly than particle-particle interactions can smooth out the energy distribution. ECR ion sources are susceptible to this since scattering cross-sections rapidly decrease with kinetic energy. For advanced sources electron energies can reach the low MeV range, and electrons with energies of 10s of keV or more will spend significant portions of their millisecond-time-scale lifetimes without collisions. If an ECR ion source is tuned in a manner that allows for the rapid heating of a significant percentage of electrons to energies where scattering becomes rare, kinetic instabilities become increasingly likely.

SINGLE PASS HEATING

The most effective heating of low-energy electrons takes place where the local magnetic field matches the injected microwave frequency, and as the energy is increased relativistic effects will move the resonance to higher magnetic field surfaces. A rough estimate of the energy gained in crossing the resonance surface can be made as follows. The differential energy gain along path length $d\vec{s}$ is given by $dE = \vec{F} \cdot d\vec{s}$. Maximum electron resonant heating in a magnetic field occurs for a circularly polarized wave of magnitude E in phase with an electron rotating at radius r through an angle $d\theta$: $dE = eErd\theta$. We can use the fact that the transverse and longitudinal (defined to be z-direction) velocities are given by $v_\perp = r\frac{d\theta}{dt}$ and $v_\parallel = \frac{dz}{dt}$, respectively, to rewrite the energy gain as $dE = eE\frac{v_\perp}{v_\parallel}dz$. Reasonable maximum microwave electric fields within the source are likely 10s of kV/m, and for typical high-charge-state producing fields (minimum-field-to-lower-mirror-field ratios of .25 to .4) the velocity ratios are in the range $.5 \lesssim \frac{v_\perp}{v_\parallel} \lesssim .8$. Plugging this all in, it is expected that energy-gain-per-mm of axial travel is in the range of 10s to 100s of eV/mm with higher gains possible as the velocity ratio increases. Single particle simulation agrees with these numbers. For a low-energy electron to reach 10s of keV kinetic energies or greater requires many such crossings, and phase differences will give much lower energy gains on average. However, if regions are accessible where the electron spends a long time in resonance either because of low axial velocity or because it is in a region of near-zero gradient, much larger energy-gains-per-pass are possible.

The minimum magnetic field near the center of the source is a region with zero-gradient, but as mentioned previously it is typically 50-80% of the resonant field. Nearly all ECR ion sources utilize axially-injected microwaves and as electron energies are increased, electron axial velocities can be large enough that the Doppler shift of this incoming wave becomes significant.

In the laboratory frame, microwaves reach a source electron with frequency $f = f_o(1 - \hat{k}_{wave} \cdot \vec{\beta})$, where f_o, $\hat{k}_{wave}$, and $\vec{\beta}$ are the injected wave frequency, its direction, and the electrons velocity divided by the speed of light, respectively. An electron will be in resonance with the shifted wave if the local magnetic field satisfies the cyclotron equation, $\omega = \frac{eB_{res}}{\gamma m}$, which can be solved for the local resonant field:

$$B_{res} = \frac{\omega\gamma m}{e} = \frac{\omega_{rf}(1 - \hat{k}_{wave} \cdot \vec{\beta})\gamma m}{e} = B_{res,\gamma=1} \cdot \gamma(1 - \hat{k}_{wave} \cdot \vec{\beta}) \quad (1)$$

where ω_{rf} is injected microwave's angular frequency and $B_{res,\gamma=1}$ is the magnetic field that a non-relativistic electron would resonate at that frequency.

Increasing the minimum magnetic field decreases the kinetic energy required for a confined (outside loss cone)

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electron to be resonantly heated at the zero-gradient field near the source center. Figure 1 shows the minimum kinetic energy necessary to reach this field ratio for an extraction mirror field (B_{ext}) twice the resonant field. Higher extraction fields move this curve down, but the effect is small over the typical extraction field operating ranges for high charge state production ($1.8 \leq B_{ext}/B_{min} \leq 2.2$).

Access to the zero-gradient part of the axial field curve allows greater kinetic energy changes near this minimum. More importantly, we will see there are other heating modes that become accessible when the electrons have energies that allow them to better utilize fields lower than the injected frequency's natural resonance.

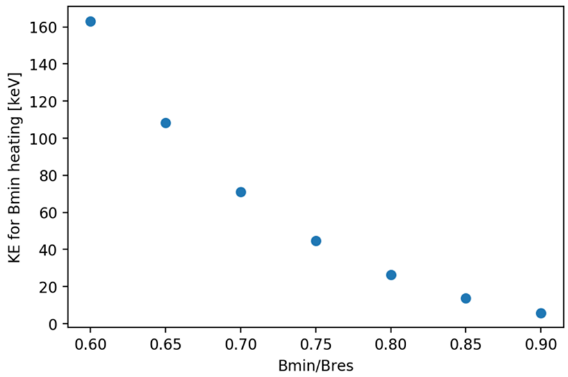

Figure 1: The minimum kinetic energy required for resonant heating at B_{min} as a function of B_{min}/B_{res} is plotted for B_{ext}/B_{res}=2.

ELECTRON RESONANT HEATING

Figure 2 shows a plot of the axial magnetic field in VENUS as a function of axial position along with the fields required for resonant heating by the Doppler-shifted injected waves a simulated, confined electron receives as it moves inside the source. The heating wave is assumed to be two axially-directed, circularly-polarized plane waves with 10 kV/m magnitude traveling in opposite directions, so at any instant the electron is affected by two waves: one Doppler shifted up and one down. Because of these shifted frequencies, the electron resonant fields are also shifted, and this shifted field is also plotted for the electron motion in Fig. 2.

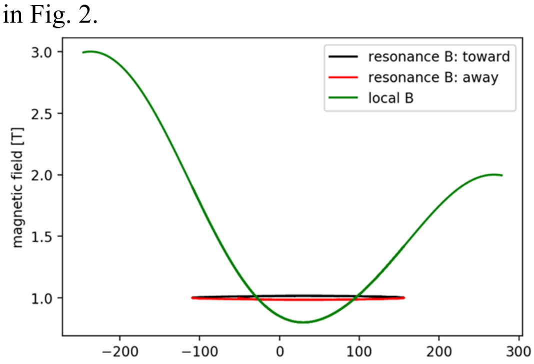

Figure 2: The axial field and Doppler-shifted resonance fields ("away": shifted down, "toward": shifted up) for a confined electron are plotted vs. axial position.

From the plot in Fig. 2, we expect resonant heating to be possible where the resonant field curves overlap with the local magnetic field. The region where these overlaps occur is shown in Fig. 3 with the energy as a function of z plotted below. As can be seen in this figure, the largest energy changes (in the range of 100s of eV, as expected) occur where the local field is close to the Doppler resonant field. For this figure and all following figures of the same format, electron energies and trajectories are selected somewhat randomly as representative of the concept, not the maximum energy gains.

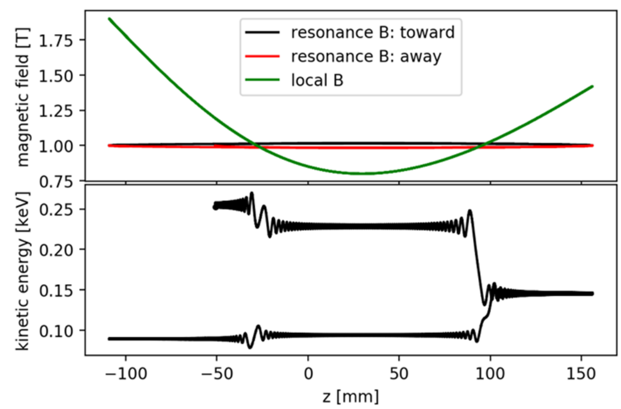

Figure 3: The axial field and Doppler-shifted resonance fields, above, and electron energy, below, are plotted vs. axial position. Energy changes occur when resonant field is near local magnetic field. This and Fig. 4-7 use semi-randomly chosen trajectories that illustrate where energy changes occur, but not the maximum energy change possible, which is phase-dependent.

As mentioned above, it is expected that if the electron spends a long period of time near resonance or interacts with regions of low magnetic field gradient, it will be possible to have especially large energy changes in a single crossing. Figure 4 shows a crossing in the former case where the electron reflection occurs near resonance. Heating in this mode, which can give higher energy changes in a single pass (~keV range) is possible for electrons of all energies in all sources with appropriate ratio of transverse-to-axial velocities, however it is expected that a small percentage of electrons have the proper angle to undergo this heating.

Increasing the minimum magnetic field provides other fast-heating mode as the lowest section of the axial magnetic field becomes accessible. Figure 5 shows what happens when the zero-gradient part of the magnetic field becomes accessible for resonant heating: larger energy gains (again, keV range or higher) become possible in a single pass.

It is not necessary for there to be actual coincident resonance near the minimum field point for there to be large energy gains. Two examples are given in Figs. 6 and 7 where the shape of the lowered resonance curve as a function of z roughly approximates the shape of the local magnetic field along the electron's trajectory. In Fig. 6 there is only one actual resonance match to the local field near each

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end of the z axis, but for the remainder of the region between these points it is near-resonance, allowing for large (keV-scale) energy gains in a single source crossing. Fig. 7 has two matches of the resonant and local fields on either side of the minimum field, but even larger gains are made possible by the outer resonances happening near the reflection points.

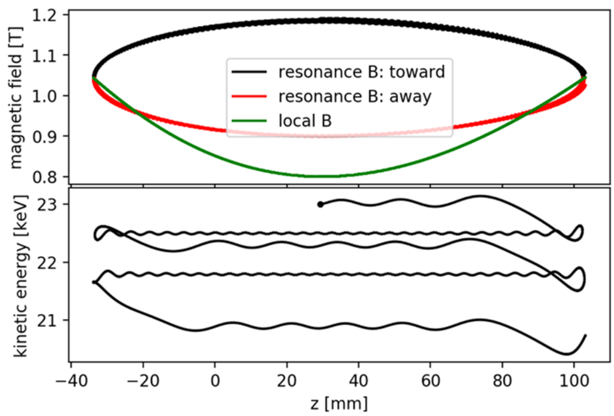

Figure 4: Resonant heating where the reflection point has a resonant magnetic field close to the local electric field. Larger energy gains are possible as the axial velocity is near zero at the ends. (see Fig. 3 for full description)

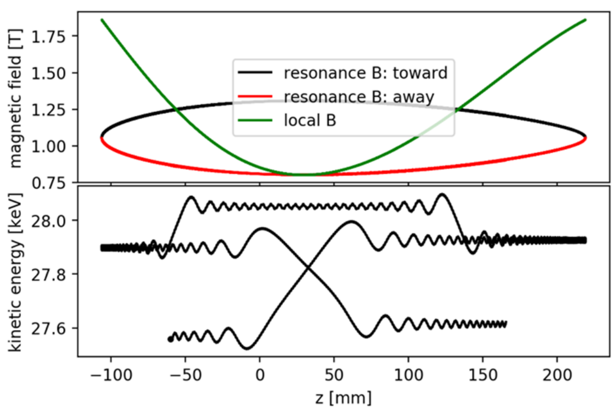

Figure 5: Resonant heating when the axial minimum becomes accessible. (see Fig. 3 for full description)

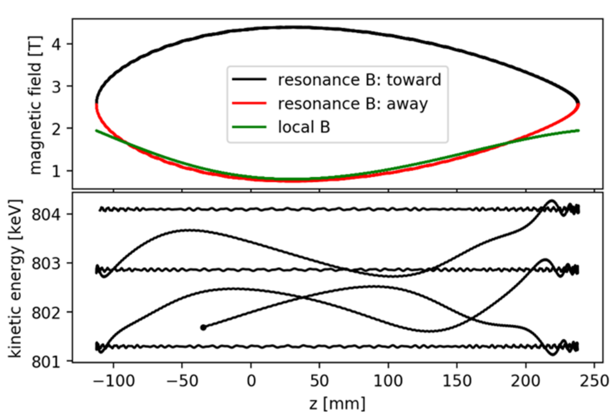

Figure 6: Resonant heating with one resonant match on either side of B_{min} but a near resonance over much of the trajectory. (see Fig. 3 for full description)

The wider availability of heating modes where large electron energy gains can be made with few axial bounces makes kinetic instabilities more probable. Increasing the minimum field makes especially high-energy-gain modes accessible at lower kinetic energy.

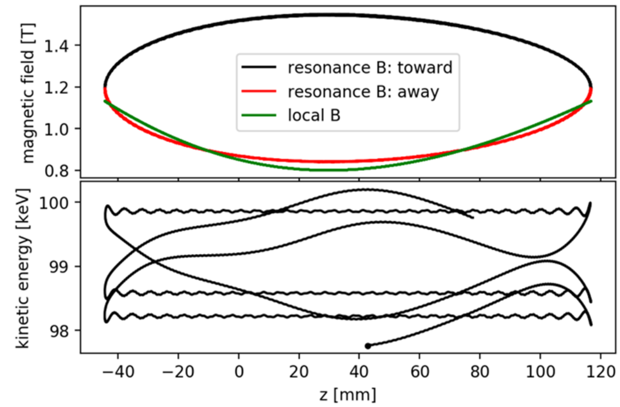

Figure 7: Resonant heating with two resonance matches on either side of the minimum field and a general shape match allowing relatively high energy changes. (see Fig. 3 for full description)

ECR RESONANT HEATING MAP

Utilizing conservation of the first adiabatic invariant ($\mu = \frac{\gamma m v_\perp^2}{B}$), it is possible to determine which near-axial electrons will encounter a resonance point before mirroring based on the kinetic energy and velocity angle away from the source's long axis at the axial location of the minimum field. Figure 8 represents a map of this kinetic energy/velocity angle phase space where resonance heating can occur for any ECR ion source with B_{min}/B_{res}=0.8 and B_{ext}/B_{res}=2.0. In this figure we can see that there is no resonant heating at large angle (electrons don't have sufficient axial velocity to reach resonance) and that the maximum energy electrons that may be resonantly heated are just over 1 MeV. The maximum bremsstrahlung energies measured from advanced ECR ion sources such as VENUS have been in the MeV range [4], and Fig. 8 implies that next-generation sources shouldn't be able to exceed this energy via resonantly heated electrons. Also plotted is the line showing the angle/energy combination allowing resonant heating at the field minimum.

For comparison, Fig. 9 shows a similar phase space plot to Fig. 8 but with a lower minimum field (B_{min}/B_{res}=0.6). It can be seen that there are a number of changes between these two plots. First, the phase space area allowing the resonant heating of confined electrons dramatically decreases when B_{min} is reduced. Second, reducing B_{min} shifts the minimum field resonance line to significantly higher energy for confined particles. Both of these would be expected to result in generally slower electron heating and lower likelihood of kinetic instabilities.

As an aside, it was found experimentally using VENUS that the instability encountered when B_{min}/B_{res}=0.8 and B_{ext}/B_{res}=2.0 went away as the extraction field was reduced to around B_{ext}/B_{res}=1.6 while keeping the minimum field

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ratio fixed. Reducing the extraction field moves the loss cone line upwards in Fig. 8, which replicates the trend when the minimum field is reduced: it shifts the kinetic energy required of confined electrons for resonance at minimum field higher and simultaneously reduces the resonant heating phase space for the confined electrons.

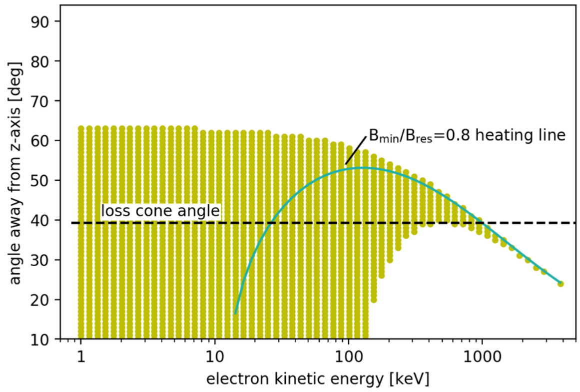

Figure 8: Phase space map indicating kinetic energy/axial angle combinations where resonant heating may occur for B_{min}/B_{res}=0.8.

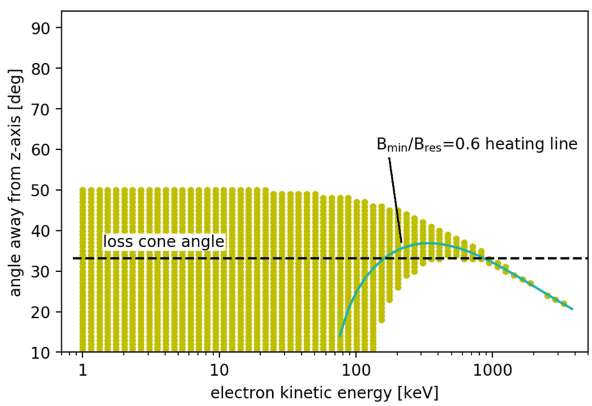

Figure 9: Phase space map indicating kinetic energy/axial angle combinations where resonant heating may occur for B_{min}/B_{res}=0.6.

ADDING SECOND FREQUENCY

The addition of a second heating frequency to an ECR ion source is a well-known means of reducing instabilities. For VENUS, the secondary frequency is 18 GHz, and Fig. 10 repeats the electron simulations above but adds 4 kV/m of the lower frequency. This represents 40% of the 28 GHz field or 16% of the power, and this power ratio is not very different from that used in VENUS.

As can be seen when comparing Fig. 10 to the earlier similar figures, the addition of the second frequency has resulted in a much noisier energy curve. We postulate here that the usefulness of the second frequency comes in its decreasing the possibility of multiple in-phase resonances from occurring as can happen with one frequency. Generally, second frequencies are used at much lower power and we conjecture that the second, lower, frequency may be able to reach to the center of the plasma more effectively than the fundamental frequency, as its resonance zone is smaller (if not non-existent). This will need to be tested experimentally.

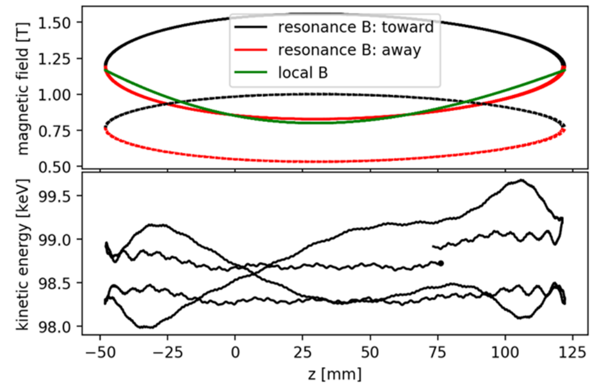

Figure 10: Resonant heating with two frequencies in VENUS (18 and 28 GHz). The resonance curve for the second, lower frequency is the lower oval-like shape in the upper plot. (see Fig. 3 for full description)

FUTURE STEPS

This analysis indicates that raising the minimum magnetic field in an ECRIS could leave the plasma more susceptible to kinetic instabilities as fast-heating modes become more easily accessible at lower energies. More statistics are needed for the simulations and if there are hopes of being accurate in our results we will need to have a better idea of injected microwaves' distribution, both in terms of position and magnitude. As we improve on these fronts, we will use this model to compare with other experimentally seen phenomena such as the seemingly periodic changes in source performance as axial magnetic fields are changed and the resonance zone's length and endpoints change which may indicate more effective heating modes.

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