MAXIMUM BREMSSTRAHLUNG ENERGY VERSUS DIFFERENT HEATING LIMITS*

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Abstract

A comprehensive set of bremsstrahlung measurements has been performed at JYFL (University of Jyväskylä, Department of Physics) in order to understand the parameters affecting the heating of electrons. In order to extend the understanding of electron heating, a new set of measurements with the JYFL 6.4 GHz ECRIS has been conducted to study the parameters affecting the maximum bremsstrahlung energy. During the work the effects of microwave power and magnetic field were studied. The analysis of the experimental data focuses in comparing the results with theoretical stochastic electron heating limits.

INTRODUCTION

In addition to the high requirements for the magnetic fields in 3rd generation superconducting ECR ion source the total microwave power fed into the plasma chamber can be even 10 kW. Consequently, these operation conditions results in intensive bremsstrahlung emission, which gives an extra heat load to the cryostat. It has been attempted to decrease the load by increasing the x-ray shielding as has been done for example for VENUS at LBNL, Berkeley using 2 mm tantalum sheet. However, due to the very limited space the thickness of the shielding must be small and thus practically transparent to the high-energy part of photon spectrum.

Experiments studying the parameters affecting the bremsstrahlung emission have been performed in several laboratories. In addition, different simulation codes have been developed to model the electron heating process. The research work has clearly shown that the magnetic field structure has a strong effect on the energy of the bremsstrahlung emission. It is explained that this is due to the lower magnetic field gradient in the heating zone, which improves the heating efficiency. As an example, the measurements at Berkeley showed that the end-point energy of the photon emission almost doubled when the B_{min} of the VENUS was increased from 0.44 T to 0.64 T having total microwave powers of 8.8 kW and 6 kW, respectively [1]. It has also been shown that the microwave power increases both the end-point energy and especially the yield of the photon emission. The build up of hot electron population in ECRIS plasma has been studied also by S. Gammino et al. [2] using Canobbio theory where maximum energy W_{max} can be expressed as $W_{\max}(eV) = 1.5 \cdot 10^9 (E(V cm^{-1})/\omega_0)^{2/3}$. In this equation E is the electric field, ω_0 the microwave frequency and it is assumed that the ECR heating takes place in a so-called low gradient regime.

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These problems and observations gave a motivation to study the bremsstrahlung emission of an ECRIS also at JYFL. The objective of the work is to study parameters affecting the high-energy bremsstrahlung radiation. This work includes developing a hybrid simulation code [3], time resolved bremsstrahlung experiments (see e.g. [4]), and as a recent effort studying the parameters affecting the end-point energy of photon emission in continuous operation mode. In this article we present some results obtained when the ion source parameters affecting the end-point energy of bremsstrahlung radiation in steady state conditions have been varied. The results were compared to a stochastic heating limit theory in order to get more insight in the possibilities affecting the production of bremsstrahlung.

STOCHASTIC HEATING LIMITS

The ECR heating is considered to be stochastic if the phase between the electron and the wave is random in consecutive passes of resonance regions. When the electron gains energy the time between the successive passings of the resonance region decreases resulting to eventual loss of phase randomization, i.e. heating is not stochastic anymore. However, the energy can be increased even further until so-called adiabatic heating limit is reached. In this work the maximum bremsstrahlung energy produced by the JYFL 6.4 GHz ECRIS has been compared to the stochastic heating theory presented in ref. [5]. The theory states that the stochastic heating limit can be expressed as

$$W_s = 0.2\left[m_e L\left(1+\frac{l^2}{L^2}\right)\right]^{1/4} l\omega^{1/2}(eE)^{3/4} \quad (1)$$

where E is the electric field of the microwaves at the resonance, $\omega = 2\pi f$ (f is the microwave frequency), m_e the mass of the electron, e is the unit charge, L is a parameter, which can be calculated from the axial magnetic field profile ($B = B_{\min}(1+z^2/L^2)$), where the resonances are at $z = \pm l$. Here B_{min} is the minimum magnetic field and z the axial distance from this minimum. Adiabatic heating limit is defined to be $W_a = 5W_s$. With the aid of equation (1) the effect of electric field E (related to microwave power), gradient of the magnetic field B, microwave frequency f and axial distance l of resonance points (from B_{min}) on the adiabatic and stochastic limits can be studied. The *gradB* has been calculated from the magnetic field profile equation shown above. In this consideration the relativistic effect, power absorption and mode structure behaviour are neglected.

Figure 1 shows the adiabatic heating limit as a function of the electric field of microwaves at the resonance. The calculations correspond to typical operation parameters of the JYFL 6.4 GHz ECRIS, i.e. *gradB = 1.5 T/m*, B_0 = 0.178 T and length *l* = 69 mm. Figure shows that using these values the typical experimental maximum bremsstrahlung energy of about 400 keV is reached with the electric field of about 1000 kV/m. The effects of length *l* and *gradB* on the adiabatic limit have been studied using this value for the electric field E. The effect of frequency *f* is omitted because of fixed frequency.

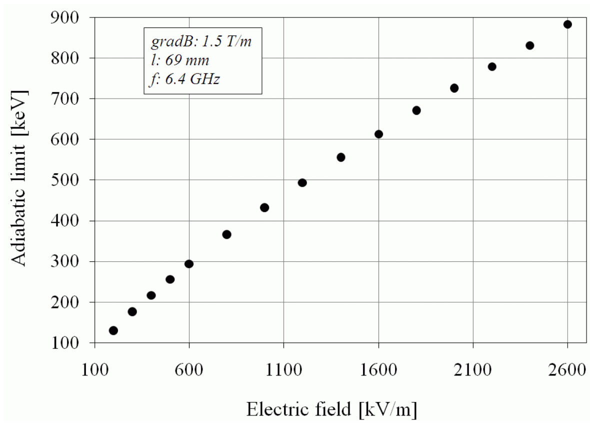

Figure 1: Adiabatic heating limit as a function of electric field *E* in the heating region.

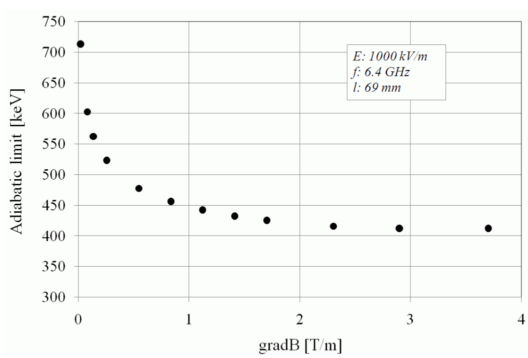

Figure 2: Adiabatic heating limit as a function of *gradB*.

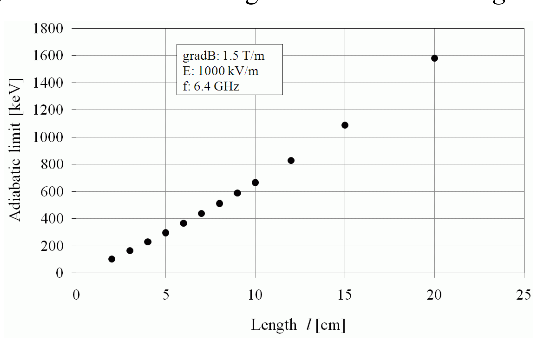

Figure 3: Adiabatic heating limit as a function of length *l* (*l* = distance between B_{min} and resonance zone).

Figure 2 shows the adiabatic heating limit as a function of *gradB* in the resonance region. The behaviour shows that the adiabatic limit starts to increase vigorously with relatively low values of *gradB*. However, these values are not reached in the resonance with the typical magnetic field settings of the JYFL 6.4 GHz ECRIS. The values of electric field *E*, frequency *f* and length *l* were kept constant resulting in unoptimized B_{min}/B_{res} -values (from 0.44 to 0.99). Figure 4 shows that the plasma size has a strong effect on the adiabatic heating limit. The 3rd generation ECR ion sources tend to have relatively large dimensions of the magnetic field, which can also explain the increase of measured bremsstrahlung energies. The larger distance between the resonances makes it possible to maintain stochastic heating at higher energies.

EXPERIMENTS

As Equation (1) shows four parameters are affecting the adiabatic heating limit in the heating region: electric field *E*, microwave frequency *f*, *gradB* and plasma size related length *l*. The validity of Eq. (1) was studied by extracting the end-point energies of the wall bremsstrahlung spectra produced by the JYFL 6.4 GHz ECRIS. The collimated photon emission was measured in the radial direction using Ge-detector. In reality this is not a true parametric study because it is virtually impossible to change only one parameter. For example, the changes in the magnetic field affect *gradB*, length *l* and consequently the electric field *E* simultaneously. In addition, the equation does not take into account the relativistic effect, which affects the effective length of *l* and *gradB* of the high-energy electrons. The heating can be limited also by the value of the maximum magnetic field and due to the increase of plasma density as a function of microwave power.

Figure 4 shows the experimental end-point energy of bremsstrahlung spectrum as a function of microwave power. As a comparison it also shows the heating limits estimated using Equation (1). The theory overestimates the adiabatic limit as can be seen in Figure 4. This might be due to the fact that the absorption of the electromagnetic wave in the resonance is not included. A new estimation was done starting with the Poynting vector and by including the Budden tunneling factor $P_t / P_0 = e^{-\pi\eta}$ for transmitted power, i.e.

$$E = Q\sqrt{\frac{2P_0 e^{-\pi\eta}}{\varepsilon_0 c \pi r^2}} \tag{2}$$

where *r* is the radius of plasma chamber, *Q* is the quality factor and $\eta = n_e/(\epsilon_0 c|dB/dz|_{res}) = \alpha n_e$. The equation shows that the power absorption improves when *gradB* decreases. The measurements have shown for the ion source settings presented in Figure 4 that the bias disk current is proportional to $P^{0.27}$, where *P* is the microwave power. The power of *P* slightly varies with the operation parameters of the ion source. Now, assuming that the plasma density n_e is proportional to the bias disk current (i.e. $n_e = aP^{0.27}$, where *a* is the fitting parameter) and that stochastic limit W_s in Eq. (1) is proportional to $E^{3/4}$ the final form of the maximum energy is

$$W_{\max} = AP^{3/8}e^{-BP^{0.27}} \tag{3}$$

where A = 95 and B = 3παa/8 = 0.16. As Figure 4 shows the fitting follows very closely the experimental data points if the power absorption of the electromagnetic wave is included. In this treatment the constant Q value is assumed for simplicity.

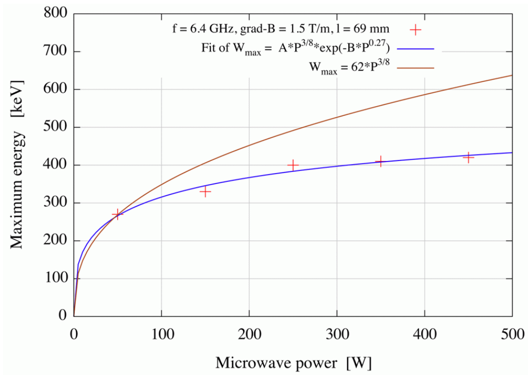

Figure 4: Maximum bremsstrahlung energy as a function of microwave power *P*.

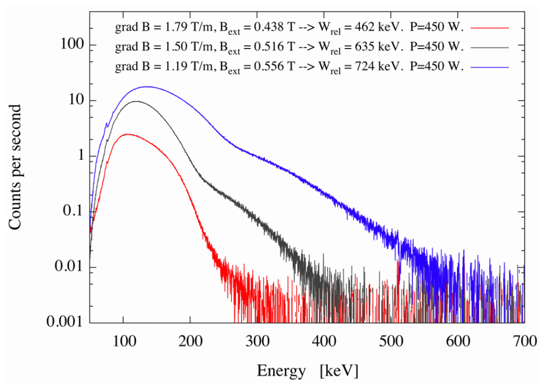

Figure 5: Effect of magnetic field settings on the bremsstrahlung energy and count rate.

Figure 5 shows the bremsstrahlung spectra for three different magnetic field configurations and Table 1 shows the corresponding data. As figure shows both the photon emission and the maximum energy increase when the B_{min} increases, i.e. the highest $W_{end\text{-}point}$ and the photon emission intensity are obtained with the lowest *gradB* value. However, in the case of conventional ECR ion source it is impossible to change only the *gradB*. Instead, the length *l* is also changed. In addition, it is possible that the electric field *E* is also changed due to changes in the plasma parameters. Consequently, the experiment cannot be used to define if the increased $W_{end\text{-}point}$ energy is caused because of decreased *gradB*. As Table 1 shows the equation (1) fails to predict the maximum energy seen in the bremsstrahlung spectrum (compare $W_{end\text{-}point}$ and W_a). This is discussed in the discussion chapter.

Table 1: Table shows the data corresponding to Figure 5. The energies $W_{end\text{-}point}$ are estimated from spectra shown in Figure 5, W_a is the adiabatic heating limit and $W_{rel,max}$ is the energy corresponding to resonance at B_{ext}.

$gradB_{res}$ [T/m]	B_{min} [T]	B_{ext} [T]	l [mm]	$W_{end\text{-}point}$ [keV]	W_a [keV]	$W_{rel,max}$ [keV]
1.19	0.199	0.556	52.4	620	322	724
1.50	0.178	0.516	68.9	420	431	635
1.79	0.146	0.438	94.6	310	619	462

DISCUSSION

As Figures 5 and Table 1 show the equation (1) fails to estimate the maximum energy of bremsstrahlung spectrum. By increasing the Bmin field the gradB has been decreased. According to the consideration based on Equation (1) this should increase the end-point energy of bremsstrahlung spectrum. This agrees with the experiments. However, at the same time the size of the plasma, i.e. length l, has decreased substantially as is presented in Table 1. Consequently, the calculated adiabatic heating limit Wa decreases, which disagrees with the experiments. One possible explanation is that the equation does not include relativistic effects.

In the case of high electron energies the mass has increased and consequently the resonance takes place at higher magnetic field values. This means that the distance between B_{min} and B_{res} for relativistic electrons increases. Due to the larger distance between the resonances the heating remains stochastic with higher electron energies – as is supposed by Eq. (1). In this consideration we have focused only on the extraction side of the JYFL 6.4 GHz ECRIS for two reasons: 1) $B_{ext} \leq B_{rad} < B_{inj}$, i.e. the extraction side limits the size of the maximum closed resonance surface and 2) the radial magnetic field profile cannot be estimated using Equation (1) because in the radial direction there are the components of axial and radial magnetic field. For the settings shown in Fig. 2 the distance between the B_{min} and B_{res} has increased from 68.9 mm for cold electrons to 132 mm for the 300 keV electrons. By increasing the energy further the resonance finally takes place at the extraction of the source and consequently the fixed maximum length l = 210 mm has been reached. This also corresponds to largest closed resonance surface. The energy corresponding to resonance at B_{ext} has been denoted by $W_{rel,max}$ in Table 1. If in Eq. (1) it is justified to use the length l for relativistic electrons the heating limit increases substantially as can be seen in Fig. 3. As a result it is possible that the adiabatic heating limit is not reached with the JYFL 6.4 GHz ECRIS because the maximum energy is limited by the magnetic field structure. It should be noticed also that if the relativistic length l is used much lower electric field of microwaves is needed to reach the same experimental end-point energy. For example, the energy of about 400 keV is reached with the electric field of the order of 100 – 200 kV/m if the length of l = 210 mm is used.

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