Gas-Mixing: Ion Cooling or Reduced Turbulent Heating?

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Abstract The question posed in the title concerns the explanation of a well-practised technique in ECR ion sources for increasing the output of the highest charge states of the ions of interest. For a long time the most accepted model was that of ion cooling, being a 'single-particle' effect. Two recent papers, likely inspired on earlier work, are proposing a 'collective' effect due to non-linear plasma-wave interaction, giving rise to turbulent heating. The mixing gas will in that picture reduce the heating. A few experiments are suggested to help unravel the problem of stating which effect is dominating.

Key words ECR ion source plasma, gas-mixing, ion-cooling, turbulent heating

1 Introduction

The mechanism of 'Turbulent Heating of Ions in a Gas-mixture' was recently presented at the International Conference on Ion Sources (ICIS05) by Elizarov et al[1] (Kurchatov Inst. Moscow). The authors claim that this mechanism is important for the ion confinement in ECRIS. Shortly later a review paper[2] by Ivanov (same institute) and Wiesemann (Bochum) appeared in IEEE Transactions on Plasma Science. These authors emphasize the occurrence of non-linear plasma – wave interaction, including the role of turbulent heating in gas-mixtures. In short they find in a gas-mixture a stronger damping of turbulent waves than in a pure gas, resulting in lower amount of heating of the heavier components, and by that better confinement and thus higher charge states in the mixture.

After discussion[3] with the authors on some details of the paper, in particular on the question of how they viewed the up to now accepted explanation[4] of gas-mixing by ion cooling, the present author has tried to define an experiment that could help to determine which is the (dominating) mechanism. The results certainly could abandon the somewhat subjective arguments that sometimes are playing a role. It is his subjective opinion that both mechanisms could be active.

Without going in detail it is clear that a difficult experiment[5] where one could determine the ion temperature in the plasma, either pure or gas-mixture, will even be not sufficient. Both models explain the increasing high charge state current by gas-mixing as the result of better confinement due to lowering of the ion temperature. So if experimentally in the case of gas-mixing a lower temperature is being found, it still could be due to either reduced heating or to better cooling.

In the following the ideas and some details for both models will be discussed shortly. Of course, the reader will need the various references for more details, in particular on theory. Using this a few suggestions are given for experiments aiming for better understanding of what is going on.

2 Details of the turbulent heating model

Low frequency ion sound noise will appear in electron cyclotron resonance systems. This was predi-

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cted, and checked experimentally in 1970 (see Ref. [2]). It occurs due to parametric instability of the pumping electromagnetic wave propagating along the magnetic field in the trap. Measurements with the ECRIS2 at Bochum[6] show - above a threshold in RF power and at certain gas pressure - two kinds of emitted noise spectra: (1) at high frequencies (GHz range, close to but below the pump frequency of 10GHz) and (2) at lower frequencies, in the 0—200MHz range. This part of the spectrum is called "ion sound" in fusion plasmas. Note that ion cyclotron resonance frequencies are in this range.

The authors of Ref. [6] suggest that ions in the plasma are being heated due to (linear) Landau - damping of this ion sound. Moreover they show that the heating is mass dependent in such a way that the lighter ions in the plasma are more heated than the heavier ions. Since the characteristic heating time constant is smaller than that of ion-ion collisions, they proposed a higher ion temperature for the light ion component and a lower temperature for the heavier component (therefore better confinement).

So the new explanation of gas-mixing, proposed in Ref. [6] is based on the (collective) effect of occurrence off parametric decay, in conjunction with different ion temperature due to mass dependent heating rates. Due to mixing with a lighter gas the ions of interest would be less heated, thus acquiring a lower temperature than compared to the case without gas-mixing. Even a small decrease can have a substantial effect, because of the strong dependence of the ion confinement τ_i on T_i. In Ref. [1] this has been worked out on the basis of new acquired theories, and quantitative expressions for the heating rates due to (non-linear) Landau damping could be derived.

3 Details about the ion cooling model

In elastic ion-ion collisions in the plasma (kinetic) energy is being transferred from the heavier to the lighter ion. If the lighter ion is escaping from the plasma - this is certainly easier for light ions in low charge state than for ions with higher charge - the effect is that the total ion kinetic energy, thus the ion-temperature, becomes lower. Therefore the role of the mixing-gas is like that of a "coolant". Here it is assumed that due the many ion-ion collisions (long range) all ions have same temperature T_i. Note that this is a "single particle description".

As in the discussion above on turbulent heating, even a small temperature decrease can have a substantial effect, because of the strong dependence of the ion confinement τ_i on T_i. According to Ref. [5]:

$$\tau_i^q(:)T^{-3/2}A_i^{1/2} \quad \text{or} \quad \tau_i^q(:)T^{-5/2}A_i^{1/2} \ ,$$

depending on the plasma region.

Therefore: the gas will be ionized, but the lower charged ions will for a relatively large extent be lost from the plasma. A smaller fraction of higher charged ions of the mixing gas will remain, as compared to the situation were the source would be operated with the mixing gas only. Without the mixing gas, the cooling of the plasma ions has to be performed by escaping lowly charged beam gas ions, but trivially this process is preventing further ionization on the way to production of the highest charge states.

The equivalence of this cooling mechanism to that of evaporative cooling applied in electron beam ion sources (EBISs) has been demonstrated by R. Becker[7].

4 Ideas for some experiments

a) Isotopic effect

In earlier experiments[8, 9] to find the nature of the gas-mixing mechanism the so-called oxygen anomaly was found experimentally. In short: the current ratio of $^{18}O^{q+}/^{17}O^{q+}$ is increasing with q, and for $q > 5$ the ratio is significantly larger than the ratio of the isotopic fractions in the feed-gas. (The same statement is true for the ratio $^{18}O^{q+}/^{16}O^{q+}$. Note that in the feed-gas just these three oxygen isotopes were present).

The authors in Ref. [8] argued that - based on confinement times being dependent on the square root of the ionic mass - the observed anomaly could only partly be explained by the ion-cooling model. For the Bochum group this was reason to study the anomaly - in their case for a ^{15}N / ^{14}N mixture (Ref. [6]) with different mixing ratios - and try to explain it with the model of (mass dependent) heating of ions by the parametric decay waves. The anomaly is subject of discussion in Refs. [1] and [2].

Can one calculate the different heating rate? Unfortunately this is not the case, since $\Delta A/A \ll 1$. Therefore it might be worthwhile to study the ECRIS performance for production of $He^{2+}$and He^{1+} in the case of natural ^4He gas as compared the case of mixing of ^4He with ^3He. Here we have the largest $\Delta A/A$, so this might be possible to use for further calculations. It would be useful to include measurement of noise spectra, in particular below and above the threshold.

b) Measuring the ion temperatures

As shown above, the ion temperatures in a multi-component plasma can be different due to difference in heating rate. Therefore a set up where one can measure with great accuracy the energy spread[10] of the produced ion beams could be used to estimate the ion temperature behaviour. Of course there are (possibly too many) pitfalls here, like extraction effects, emittance contributions etcetera.

c) External noise generation

This will - of course in terms of ion heating - never help to improve the production of heavier highly charged ions. But it would be interesting to try to add noise in the frequency range that is being absorbed by heating of the mixing gas ions. That would perhaps eliminate the influence of the mixing gas and bring the plasma back in the status comparably to that without the mixing gas, i.e. increase the heavier ion temperature.

Such experiments have been performed earlier by the Bochum group1). It would be valuable to perform such an experiment with a well performing ECRIS, and using state of the art noise generator and detector in the MHz range. Here it will be extremely interesting to study the effects just below and above the threshold for occurrence of the parametric decay.

d) Testing thresholds

In a set-up as mentioned in the previous paragraph one could focus on two questions: (i) is there indeed a threshold in RF power for occurrence of parametric decay? (ii) is there a threshold in RF power for gas-mixing? If the answers are different, then a new situation appears!

5 Conclusion

It seems that there is no simple reason to state which of the two models that describe the mechanism of the gas-mixing process is dominating. The experience obtained in many experiments has really given many “prescriptions” for choosing the best combination of beam-gas and mixing-gas, and for tuning of the ion source parameters. To the author’s knowledge, all of these were not in conflict with the “ion cooling” model. It can very well be that these prescriptions are applicable for the “reduced turbulent heating” model as well. It is tried to describe experiments that could shed more light on the validity of the two models. In case of preference for the reduced turbulent heating model, one could imagine to equip a source with new other means to absorb the occurring ion sound –without feeding an extra mixing gas – and thereby still creating some means of reducing the ion sound energy, thus lowering the ion temperature.

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