Elevated Ion Temperature in a
Double-Ended Q-Machine

Ian G. Brown

IPP II/207

Nov. 1971

MAX-PLANCK-INSTITUT FÜR PLASMAPHYSIK
GARCHING BEI MÜNCHEN

MAX-PLANCK-INSTITUT FÜR PLASMAPHYSIK
GARCHING BEI MÜNCHEN

Elevated Ion Temperature in a
Double-Ended Q-Machine

Ian G. Brown

IPP II/207

Nov. 1971

*Die nachstehende Arbeit wurde im Rahmen des Vertrages zwischen dem
Max-Planck-Institut für Plasmaphysik und der Europäischen Atomgemeinschaft über die
Zusammenarbeit auf dem Gebiete der Plasmaphysik durchgeführt.*

ABSTRACT

The perpendicular ion temperature of a barium plasma contained in a double-ended Q-machine has been measured by a spectroscopic technique. When the plasma is "ion-rich" good agreement is found between the measured ion temperature and the hot-plate temperature, while in the "electron-rich" regime the ion temperature is elevated above the hot-plate temperature. The increased ion temperature can be well accounted for by the energy input through the acceleration of ions through the electron sheath and their consequent thermalisation.

I. INTRODUCTION

The plasma contained in a Q-machine¹ is produced by direct contact ionisation of neutral atoms on a heated end-plate. Because of this simple creation process, it was originally assumed that the ion (and electron) temperature in such a device must equal the temperature of the ionising hot-plate. More recently,²⁻⁵ it has been recognised that in some circumstances it is possible for the ion temperature to significantly differ from the plate temperature. In particular, in the case of an electron-rich plasma (plasma potential negative with respect to plate potential) contained in a double-ended Q-device, ions born in thermal equilibrium with the hot plate are accelerated through the sheath potential drop into the plasma. If the ion-ion collision mean free path is not too long, this directed energy will thermalise, resulting in a temperature of ions elevated above that of the end-plate. It is thus of some interest to measure the ion temperature as a function of sheath potential, and to determine whether the observed temperature increase can be adequately explained by the theoretically predicted² extra energy input from the sheath acceleration. Such an experiment has recently been reported by Motley and Kawabe.⁶ They have measured the perpendicular ion temperature of a cesium plasma contained in a double-ended Q-machine, using an ion sensitive probe invented by Katsumata and Okazaki.⁷ Though their results show the expected qualitative behaviour with respect to sheath potential, the measured temperatures are consistently higher than those predicted. The use of a probe which must be physically inserted into the plasma in order to measure ion temperature gives rise to all the usual problems associated with perturbing

probes, and the use of a non-perturbing diagnostic has obvious advantages. The measurements reported on here employ such a method.

The perpendicular ion temperature is obtained, essentially from a Doppler broadening measurement, using a Zeeman scanning technique to trace out the line shape of the plasma Ba^+ ion resonance line at $\lambda 4934 \text{ \AA}$. Measurements have been made over a wide range of plate temperature and ion density, covering both the ion-rich and electron-rich regimes, allowing a quantitative comparison of the results to the theory of von Goeler and Motley.² Good agreement is found between the experimental results and the predictions of the theory.

II. THEORY

The elevation in ion temperature of a collision dominated plasma contained in an electron-rich, double-ended Q-machine has been considered theoretically by von Goeler and Motley.² They assume that the incoming ion flux, Γ_i , is balanced by a recombination flux on the end-plates, Γ_0 , plus an additional radial loss flux $L = nl/\tau$, where n is the ion density, l the plasma column length and τ the ion confinement time. τ refers to all non-equilibrium losses, and is here dominated by the $\underline{E} \times \underline{B}$ losses. The incoming ion energy flux is taken to be $\Gamma_i(2kT_p + eV)$, where T_p is the hot-plate temperature and V the sheath potential, and, for the case where energy loss from ions to electrons is negligible, is balanced by an energy loss, per plate, of $\Gamma_0(2kT_i + eV) + \frac{3}{2}kT_i \cdot nl/2\tau$. Thus ions are assumed to enter the plasma with an energy corresponding to a half Maxwellian at the end-plate temperature, accelerated through the sheath drop V_i ; the energy loss per particle to the end plate, $2kT_i + eV$, is

considered to be a good approximation so long as the ion drift velocity $v_D \ll [kT_p + eV/m]^{1/2}$. Each particle lost radially removes an amount of energy $\frac{3}{2}kT_i$.

From these two particle and energy balance equations, and using also the usual expressions for the particle balance on the hot-plate surfaces,^{8,9} an expression is derived from which the ion temperature can be obtained:

$$\frac{2l}{rv_i} = \frac{2\left(\frac{T_p}{T_i} - 1\right)\left(\frac{n}{n_0}\right)^{\frac{T_p}{T_i}}}{\left(\frac{T_p}{T_i}\right)^{1/2}\left(\frac{3}{2} - 2\frac{T_p}{T_i} + \frac{T_p}{T_i} \ln \frac{n}{n_0}\right)} \quad (1)$$

where $v_i = (8kT_p/\pi m_i)^{1/2}$ and n_0 is that density at which the sheath vanishes and is given by the Richardson current from the hot-plate,

$$\begin{aligned} n_0 &= 4j_{Ri}/v_e \\ &= 4AT_p^2 \exp(-eW/kT_p)/v_e \end{aligned} \quad (2)$$

The expression (1) is valid only for $n \leq n_0$.

The results are given in the form of plots of T_i/T_p vs n/n_0 for various values of the loss parameter $2l/rv_i$. For the purposes of the present experiment, equation (1) has been numerically solved using the experimentally determined value of the loss parameter, and it is this solution which is referred to later in comparing the experimental results with theory.

The foregoing treatment concerns itself only with the additional energy input to the plasma from the axial electric fields present at the hot end-plates. It is possible that radial electric fields, due to hot-plate temperature non-uniformities and to the radial density gradient, can also contribute to the total energy input to plasma ions. Estimates of the

energy input in the different radial regimes of the plasma column have been made by several authors,^{10,11} and a concise summary of these effects is given by Motley and Kawabe.⁶

Briefly, in the central body of the plasma (where $E_r \neq 0$), there is an increment of perpendicular ion temperature due to the radial electric field of amount

$$\frac{\Delta k T_{i\perp}}{k T_{i\perp}} \approx \frac{1}{4} \left(\frac{\rho_i}{\lambda} \right)^2, \quad (3)$$

where ρ_i is the ion cyclotron radius and λ the density relaxation length. Energy input due to ion viscosity in the region near the limiting aperture can also be estimated, but the uncertainties here become great, and it is perhaps better to rely on the experimental results to conclude whether or not these additional effects are important.

III. EXPERIMENTAL

The measurements were made using the Q-machine "BARBARA".¹² The plasma is confined axially by two rhemium end-plates of 3.2 cm. diameter (with 3.0 cm. diameter limiters) and 50 cm. apart, and radially by a homogeneous magnetic field of 2.5 KG (for these experiments). The end-plates can be heated up to $\sim 2500^\circ\text{K}$, the absolute temperature and temperature distribution being pyrometrically determined. The machine can be operated either single-ended (only source end-plate hot) or double-ended (both end-plates hot). Ion density was measured using a Langmuir probe, and for these experiments was varied between $2 \times 10^{10}\text{cm}^{-3}$ and $1.5 \times 10^{11}\text{cm}^{-3}$. Typical radial profiles of ion saturation current and of floating potential are shown in Fig. 1. A

metallic disc temporarily inserted into the plasma column and biased to collect ion saturation current allowed a determination of the total ion input flux, ϕ_i , which together with the measured ion density, n_i , yields an experimental value for the ion containment time, τ : $\tau = n_i V / \phi_i$, where V is the plasma volume. Under the conditions for this experiment the ion containment time was always $\tau = 3.0 \pm 0.5$ msec. Within experimental uncertainties, this is in agreement with the Bohm containment time expected for these conditions, implying that anomalous radial diffusion is indeed the dominant loss mechanism.

The ion temperature has been obtained using a method^{13,14} in which the Doppler broadened line width of one of the plasma Ba^+ ion resonance lines ($6^2S_{1/2} - 6^2P_{3/2}$, $\lambda 4554 \text{ \AA}$, or $6^2S_{1/2} - 6^2P_{1/2}$, $\lambda 4934 \text{ \AA}$) is measured using a Zeeman scanning technique. An external source is used to provide a line of very narrow linewidth which is passed through the plasma and the absorption measured. The probing line is then Zeeman scanned across the plasma line by a magnetic field surrounding the external source. A plot of absorption vs. wavelength shift is so obtained, which can readily be related to the plasma ion temperature. The two Ba^+ ion resonance lines suffer an anomalous Zeeman splitting, as is shown in Fig. 2. Thus in reality one may have as many as six "probing" lines (not necessarily of equal intensity) scanning simultaneously six plasma lines; this results in only a minor complication in interpretation. For "typical" plasmas, say $T_i \sim 2000 \text{ }^\circ\text{K}$, the Doppler halfwidth is $\sim 13 \text{ m\AA}$, and it is clear that by using an appropriate choice of source and plasma line polarisations, a plasma in a magnetic field can be adequately scanned by a lamp field varying up to only about one half of the plasma field. The resultant absorption profile depends, of course, on

the particular conditions chosen. In general, for a given experimental situation (plasma magnetic field, orientation of optical access, expected range of ion temperature) many such profiles should be computed, and that giving maximum temperature sensitivity chosen. The lamp line-width should also be folded into the calculation, if this is not negligible.

The method measures the temperature component in the direction of the beam, i.e., the perpendicular (to the magnetic field) temperature, for the set-up used here. Since the beam is passed diametrically through the plasma, the measurement is unaffected by any axisymmetric ion rotation, e.g., ion diamagnetic drift. Doppler broadening due to turbulence, on the other hand, will be measured and will result in an erroneous apparent temperature; however, the calibration of the method, described below, indicates that any such broadening is minimal and can be neglected.

The experimental arrangement used for the measurement is quite straightforward. The lamp (a commercially available hollow-cathode lamp has been used here) is located within the uniform magnetic field produced by a water cooled solenoid; ideally the lamp should be liquid nitrogen cooled. The beam is chopped and passed radially through the plasma, and detected by a photomultiplier preceded by a $5\text{\AA}$ bandwidth filter centered on $\lambda 4934\text{ \AA}$. The photomultiplier signal is subtracted from an in-phase reference signal provided by the chopper (or by another filter-photomultiplier combination monitoring a fraction of the lamp light before passage through the plasma), using a differential lock-in amplifier, and the change in the difference signal is measured as the plasma is manually chopped by a blade in front of the hot-plate. For a plasma density $\sim 10^{10}\text{ cm}^{-3}$ and a plasma diameter of several cm., the maximum absorption is only a few

percent, and a high sensitivity detection system is essential. Measurements are made for a number of lamp magnetic fields and the results compared with theoretically computed curves to find the plasma ion temperature. The method is limited to densities not much higher than $\sim 10^{11} \text{ cm}^{-3}$, above which the plasma becomes optically dense to the resonance radiation; it may be possible to use the $\lambda 6142 \text{ \AA}$ line (from a metastable state) for higher densities.

A series of ion temperature measurements have been made of the plasma formed in BARBARA when operated in the single-ended mode, in order to provide a calibration of the method. The $\lambda 4954 \text{ \AA}$ line was used with the lamp viewed end-on (i.e. light propagation parallel to lamp magnetic field) and the beam passed through the plasma perpendicular to the plasma magnetic field. Thus the lamp σ lines are scanned through the σ and π plasma lines. Typical data, together with the computed absorption curves, are shown in Fig. 3. The results of a number of such measurements, varying the hot-plate temperature over the limited range available, are shown in Fig. 4. The measured ion temperature is seen to be $\sim 10\%$ lower than the measured hot-plate temperature. Since the plate temperature is in error by no more than 2-3%, one can conclude either that the ion temperature is really equal to the plate temperature and that the method is in error, or that the method is correct and the ion temperature is somewhat lower than the plate temperature. As will be seen later, the ion temperature for a plasma contained in a double-ended device, in the ion-rich regime, is measured to be equal to the plate temperature. This offers supporting, though not conclusive, evidence that the measuring technique is correct. We conclude then, that the ion

temperature diagnostic here employed yields a reliable value for this parameter, with a possible inherent error such that the measured value is $\sim 10\%$ low.

IV. RESULTS

Typical temperature determinations for plasma contained in the device operated double-ended are shown in Fig. 5, where the (relative) fractional absorption of the probing beam is plotted as a function of lamp magnetic field. The experimental points can be well fitted by a single theoretical curve with an error in the associated temperature typically $\sim \pm 10\%$. The results of a series of measurements in which the temperature of the end plates was held constant and the ion density varied are shown in Fig. 6. As is expected, the ion temperature rises at lower ion densities, corresponding to a more negative plasma potential (relative to the hot plates) and consequently a greater sheath acceleration. The solid curve has been obtained from the theory of von Goeler and Motley using parameters appropriate to our Q-machine, (measured ion containment time $\tau = 3.0$ msec, distance between end-plates, $l = 50$ cm.); it is evident that the theoretical curve provides a good fit to the experimental data. From many such data, over a range of plate temperature $2175^\circ\text{K} \leq T_p \leq 2520^\circ\text{K}$ and of ion density $2 \times 10^{10} \text{ cm}^{-3} \leq n_i \leq 1.5 \times 10^{11} \text{ cm}^{-3}$, the results shown in Fig. 7 are obtained. Here the ratio of ion temperature to plate temperature, T_i/T_p , is plotted as a function of relative ion density, n_i/n_0 , where n_0 is that density at which the sheath vanishes, (the effective work function for rhenium has been taken as $W = 5.1$ eV)¹⁵. Again, the solid curve is obtained from the theory of von Goeler and Motley, and the fit is seen to

be good. Note that there are no adjustable parameters involved in the fitting - the experimental data and theory are in good absolute agreement. When the plasma is ion rich, the ion temperature and end-plate temperature are equal, while for the electron-rich case the ion temperature is elevated above the end-plate temperature by an amount which is consistent with that theoretically predicted from the theory of von Goeler and Motley, using the experimental value of τ , $\tau = 3.0$ msec.

V. DISCUSSION & CONCLUSION

As was pointed out in section III, it is possible that the ion temperature diagnostic method used here underestimates the true temperature by $\sim 10\%$. In this case, the data points shown in Figs. 6 & 7 should all be raised by this amount. Even should this be so, however, one must still conclude that the experimental results are in reasonable agreement with the theory used here. Moreover, any additional energy input to the plasma must be small compared (a) to the total plasma energy, and (b) to that input from the sheath acceleration. The fractional increase in ion temperature due to the radial electric field can be estimated from equation (3) to be no more than several percent. This then implies that the fractional temperature increase due to other causes - e.g., ion viscosity in the region near the plasma aperture - can also be no more than several percent. This is contrary to the results of Motley and Kawabe, who see $\sim 50\%$ "anomalous" temperature elevation. There are differences in the plasma sources used in the two experiments; the Q3 plasma column is longer than here, and the hot-plate temperature distribution is probably more uniform than that used here.¹⁶ It is, however,

difficult to speculate on specific causes for the difference. It is quite possible that the discrepancy is due, in part or in entirety, to the use of the perturbing ion sensitive probe. Such a probe has been used in the BARBARA device during the course of these experiments.¹⁷ Although an exhaustive comparison could not be made, there were cases where the ion temperature measured by the probe exceeded that measured spectroscopically by more than a factor of two. This indeed casts some doubt on the applicability of the probe in the present context. (It should be stressed, however, that in other cases - notably when the Q-machine was operated single ended, and so when thermalisation of directed ion energy cannot occur, - the ion sensitive probe yielded ion temperatures which were quite close to the hot plate temperature).

In conclusion, the ion temperature in the double-ended Q-machine BARBARA has been measured over a range of hot-plate temperature and ion density such as to include both ion-rich and electron-rich regimes, and good agreement is found with the theory of von Goeler and Motley. No evidence is seen for any substantial additional energy input to the plasma ion component from mechanisms other than that of the acceleration of ions through the sheath and their consequent thermalisation.

ACKNOWLEDGEMENTS:

The author is grateful to Dr. R.F. Ellis for many valuable discussions during the course of this work, and to L. Griffith for carrying out the numerical computations.

This work was performed as part of the agreement between the Max-Planck-Institut für Plasmaphysik, Munich-Garching, and Euratom to conduct joint research in the field of plasma physics.

REFERENCES:

ACKNOWLEDGEMENTS:

1. N. Rynn and N. D'Angelo, Rev. Sci. Instr., 31, 1326 (1960).
2. S. von Goeler and R.W. Motley, Phys. Fluids, 13, 834 (1970).
3. J.G. Hirshberg, J. Hesser, E. Hinnov and N. Rynn, Phys. Fluids, 10, 1114 (1967).
4. E. Hinnov, T.K. Chu, H. Hendel and L.C. Johnson, Bull. Am. Phys. Soc., 14, 1056 (1969).
5. M. Hashmi, A.J. van der Houven van Oordt, and J.G. Wegrowe, Symposium on One-Particle Distribution Functions in Plasmas, Marburg, August 1968, paper no. 12.
6. R.W. Motley and T. Kawabe, Phys. Fluids, 14, 1019 (1971).
7. I. Katsumata and M. Okazaki, Japan. J. Appl. Phys., 6, 123 (1967).
8. S. von Goeler, Phys. Fluids, 7, 463 (1964).
9. R.W. Motley and D.L. Jassby, Phys. Rev., 187, 314 (1969).
10. G. Grieger, in "Proceedings of the Conference on Physics of Quiescent Plasmas," (Frascati, Italy, 1967), PtI, p.67.

11. S.J. Braginskii, in "Reviews of Plasma Physics", (Consultants Bureau, New York, 1965), Vol. I, p.219.
12. M. Hashmi, A.J. van der Houven van Oordt, and J.G. Wegrowe, Nucl. Fusion, 10, 173 (1970).
13. G. Grieger and W. Ohlendorf, Bull. Am. Phys. Soc., 13, 1512 (1968).
14. I. G. Brown and W. Ohlendorf, "Tenth International Conference on Phenomena in Ionised Gases," (Oxford, 1971), p.410.
15. There is some doubt as to the correct value to be taken for the work function of rhenium. That the value chosen here results in a good fit between the experimental data and theory can be taken as supporting evidence for the correctness of this value.
16. R.F. Ellis, private communication.
17. These measurements were performed by I. Katsumata.

FIGURE CAPTIONS:

- Fig. 1. Typical radial profiles of floating potential and of ion saturation current.
- Fig. 2. Zeeman splitting of the two Ba^+ ion resonance lines (for a magnetic field of 2.5kG.)
- Fig. 3. Determination of ion temperature for the case of single-ended operation. The solid curves are the theoretically computed absorption profiles. The uncertainty in the hot-plate temperature, $\Delta T_p \approx 50^\circ\text{K}$.
- Fig. 4. Ratio of measured ion temperature to hot-plate temperature as a function of hot-plate temperature. Single-ended operation.
- Fig. 5. Typical temperature determinations for double-ended operations. The solid curves are theoretically computed absorption profiles, and the hot-plate temperature uncertainty, $\Delta T_p \approx 50^\circ\text{K}$.
- Fig. 6. Measured ion temperature as a function of ion density for a fixed hot-plate temperature of $2,520^\circ\text{K}$. (Double-ended operation). The solid curve is obtained from the theory of von-Goeler and Motley (equation (1)).
- Fig. 7. Ratio of measured ion temperature to hot-plate temperature as a function of the ratio of ion density to that density at which the sheath vanishes. Solid curve from the theory of von-Goeler and Motley.

Fig. 1. Typical radial profiles of floating potential and of ion saturation current.

Fig. 2. Zeeman splitting of the two Ba^+ ion resonance lines (for a magnetic field of 2.5kG.)

Fig. 3. Determination of ion temperature for the case of single-ended operation. The solid curves are the theoretically computed absorption profiles. The uncertainty in the hot-plate temperature, $\Delta T_0 \approx 50 \text{ }^\circ\text{K}$.

Fig. 4. Ratio of measured ion temperature to hot-plate temperature as a function of hot-plate temperature. Single-ended operation.

Fig. 5. Typical temperature determinations for double-ended operations. The solid curves are theoretically computed absorption profiles, and the hot-plate temperature uncertainty, $\Delta T_p \approx 50^\circ\text{K}$.

Fig. 6. Measured ion temperature as a function of ion density for a fixed hot-plate temperature of 2,520 °K. (Double-ended operation). The solid curve is obtained from the theory of von-Goeler and Motley (equation (1)).

Fig. 7. Ratio of measured ion temperature to hot-plate temperature as a function of the ratio of the ratio of ion density to that density at which the sheath vanishes. Solid curve from the theory of von-Goeler and Motley.