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ABSTRACT

The results of several high power neutral injection heating experiments are used to derive scaling laws for the ion temperature and the ion containment time valid for both ohmically heated and high power injection heated discharges.

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Although empirical scaling laws have been established[1,2,3] for the energy containment time and the ion temperature (T_i) in ohmically heated tokamaks, similar laws have not yet been established for tokamaks heated by high power neutral beam injection. This is partly because of the increased difficulty in making simplified plasma energy balances in these discharges. This letter uses a set of simplifying assumptions to derive scaling laws for the ion temperature and the ion energy containment time (τ_{E_i}) in injection heated discharges. This approach is an alternative to the use of 1-D simulation codes or transport analysis codes to determine the plasma energy balances.

In the derivation[2] of the scaling law for T_i for ohmically heated discharges, an energy balance is made between the power input (P_{ei}) to the ions from collisions with the electrons and the ion losses (P_L^i) which are assumed to be determined by plateau conduction losses. In high power injection heated discharges the power input to the plasma ions (P_{NI}^i) from the beam can be large enough to ensure that, at low plasma density, $P_{NI}^i >> P_{ei}$ and P_{ei} can be neglected. The simplified energy balance $P_L^i = P_{NI}^i$ can then be used to analyse the scaling of both τ_{E_i} and T_i with injection power and other parameters. This approach neglects the role of profiles and other effects in order to obtain a simple expression for the scaling laws. However, the underlying assumptions of the approach are checked using a O-D time independent energy balance. The relation of the ion losses determined from experiment to those predicted by the full neoclassical theory of ion conduction losses are discussed.

Ohmic Heating. In order to obtain an expression for the ion power losses in ohmically heated discharges, the ion temperature scaling calculations of ref.[2] have been repeated using the data set of refs.[1,3]

supplemented by further DITE data taken from refs[4,5,6]. Assuming that all profiles vary as $(1 - (r/a)^2)^2$ and that the ion collisionality parameter is in the plateau region, the power loss from the central region of the plasma ($r/a \leq 0.5$) can be written as (in mks units, T_i in eV, and assuming $q(r/a = 0.5) = q_L/2$)

$$P_L^i = \alpha \frac{T_i^{5/2} \bar{n}_e q_L \sqrt{A_i}}{B_\phi^2} \text{ W} \qquad \ldots 1$$

where T_i is the central ion temperature, $\bar{n}_e (= \bar{n}_i)$ is the line averaged electron density, q_L the safety factor at the limiter, A_i the ion atomic weight and B_ϕ the toroidal magnetic field strength. Equating P_L^i to P_{ei} ($r/a \leq 0.5$) then gives the usual Artsimovich expression[2)] for T_i, and a comparison of the calculated values of T_i with those of the data sets determines $\alpha = (5.4 \pm 0.4) \times 10^{-22}$.

Neutral Beam Heating. In injection heated tokamak discharges at low density, the ion temperature is usually raised sufficiently to take the plasma ions out of the plateau and into the collisionless regime of collisionality and the form of equation (1) needs modifying. The modified equation will be determined from experiment and, guided by the theoretical expression for the collisionless conduction coefficient[7)], it is assumed that, over a restricted range of the collisionality parameter, ν_i^*, the power loss from the ions can be written as

$$Q_i = A \, \bar{\nu}_i^{*B} \, P_L^i \qquad \ldots 2$$

where A and B will be determined from experiment. $\nu_i^* = (R/r)^{3/2} \, q \, R/v_i \tau_i$ with R the plasma major radius, v_i the ion velocity and τ_i the ion collision time[7)]. $\bar{\nu}_i^*$ is the value of ν_i evaluated at $r/a = 0.5$ and with $q(r/a = 0.5) \approx q_L/2$. A simplified power balance is then made between Q_i and the power input to the ions from the neutral injection.

$$Q_i = P^i_{NI} = f^i \; P_{NI} \qquad \ldots 3$$

where the fraction (f^i) of the total injection power (P_{NI}) transferred to the ions can be evaluated using the curves presented in ref[8)] at the average electron temperature ($\bar{T}_e = T_e(r = 0)/2$) and average injection energy.

This analysis is applied to the data set of Table 1 which includes the main parameters of well diagnosed discharges in a variety of machines. In Figure 1 the plot of $f_i \; P_{NI}/P^i_L$ against $\bar{\nu}^*_i$ determines, by linear regression, A = 0.88 ± 0.35 and B = 0.55 ± 0.12 with a correlation coefficient r = 0.75. The ISX-A points are indicated separately as the experimental values of T_i are known to be too large[17)] by 20-40%. An F-test applied to this data set shows that the fitted line is significant at the 1.0% confidence level. Hence

$$Q_i = 0.88 \; \bar{\nu}^{*\,0.55}_i \; P^i_L \qquad \ldots 4$$

This expression for Q_i equals equation (1) at $\bar{\nu}^*_i = 1.26$ and it is therefore reasonable to determine the ion losses from (1) when $\bar{\nu}^*_i > 1.26$ and from (2) when $\bar{\nu}^*_i < 1.26$. This leads to a single expression for the ion power losses

$$Q_i = 5.4 \times 10^{-22} \, \frac{T_i^{5/2} \, \bar{n}_e \, q_L \sqrt{A_i}}{B^2_\phi} \, f(\bar{\nu}^*_i) \qquad \ldots 5$$

with $f(\bar{\nu}^*_i) = 1$ for $\bar{\nu}^*_i > 1.26$ and $f(\bar{\nu}^*_i) = 0.88 \; \bar{\nu}^{*\,0.55}_i$ for $\bar{\nu}^*_i \leqslant 1.26$ and

$$\bar{\nu}_i^* = 3.49 \times 10^{-16} \left(\frac{R}{a}\right)^{3/2} \frac{\bar{n}_e \, q_L \, R}{\sqrt{A_i} \; T_i^{\,2}} \qquad \ldots \; 6$$

Calculations have shown[18)] that the value of $\bar{\nu}_i^*$ should be increased by a factor $\sqrt{2}\, Z_{eff}$ in order to include the effects of ion-impurity collisions. A repeat of the analysis leading to equation (4) including this factor shows a slightly poorer straight line fit on the $f_i \, P_{NI}/P_L^i$ versus $\bar{\nu}_i^*$ plot. It is therefore considered reasonable not to include the Z_{eff} dependence.

Scaling Laws for T_i. Equations (3) and (5) can be combined to derive a scaling law for the ion temperature in low density, high power injection heated discharges:

$$T_i = 3.2 \times 10^8 \left[\frac{f_i \, P_{NI} \, B_\phi^2}{\bar{n}_e \, q_L \, \sqrt{A_i} \; f(\bar{\nu}_i^*)}\right]^{0.4} \text{eV} \qquad \ldots \; 7$$

The comparison of this scaling law with experiment, again for the points of Table 1, is shown in Figure 2. There is good agreement.

Equating P_{ei} and Q_i gives a scaling law for T_i in ohmically heated discharges:

$$T_i = 2.57 \times 10^{-6} \sqrt[3]{I \, B_\phi \, R^2 \, \bar{n}_e / f(\bar{\nu}_i^*)} \Big/ \sqrt{A_i} \qquad \ldots \; 8$$

The constant 2.57×10^{-6} is just 6% lower than that of ref.[2)] In the region $\bar{\nu}_i^* < 1.26$ this scaling law differs slightly from the values calculated to determine α. However, the plot of calculated versus experimental values of T_i for ohmic discharges (Figure 3) shows that equation 8 is a good fit to the experimental data.

A check on the validity of the simplified calculations above is made by constructing a O-D power balance model which includes power inputs to the ions from both electron-ion collisions and from the neutral beam heating. The ion losses are assumed to be described by equation (4) and the effects of neutral beam transmission and penetration are included. This model confirms, to within 30%, the correctness of the value of Q_i given by equation (4) and justifies the neglect of P_{ei} during injection in the simplified energy balance.

Ion Energy Containment Time. A value for the ion energy containment time (τ_{Ei}) can be calculated from the plasma energy content and equation (5)

$$\tau_{Ei} = \frac{3.5 \times 10^3 \, Ra^2 \, B_\phi^{\;2}}{T_i^{\,3/2} \, q_L \, \sqrt{A_i} \; f(\bar{\nu}_i^*)} \; s \qquad \ldots 9$$

Comparison With Neo-Classical Conduction Losses. The plateau neo-classical ion conduction loss[20)] Q_i (plateau) is evaluated at $r/a = 0.5$ assuming $q(r/a = 0.5) = q_L/2$. This is compared with the empirical power loss in Figure 4 where Q_i/Q_i (plateau) is plotted as a function of $\bar{\nu}_i^*$. Also shown is the neo-classical heat conduction coefficient divided by the plateau value. If the ion heat loss is entirely due to neo-classical processes then these two curves should coincide. However, there is a considerable divergence between the curves, which increases with decreasing $\bar{\nu}_i^*$. Within the present approach the difference cannot be adequately understood, but it can be partly reduced by enhancing the collision frequency by $\sqrt{2}\, Z_{eff}$ to give, approximately, the dashed curve on Figure 4. However, the curves, in agreement with theory at high collisionalities, exceed theory by up to an order of magnitude at low collisionality. In some experiments (eg PLT[13,14]) Q_i has a large contribution from charge exchange (Q_{ex}) and convection losses (Q_D), but in other experiments (eg DITE[4]) this contribution is quite small. Because the plasma neutral density or equivalently the particle confinement time is a poorly measured tokamak parameter it is difficult to assess in a general way the magnitude of the contribution of Q_{ex} and Q_D to Q_i. It is therefore probably reasonable to regard Q_i as an upper limit for the ion conduction loss.

Summary. An analysis of high power neutral injection experiments is used to derive an expression for the ion power loss and ion energy containment time in a tokamak over a wide range of collisionality. In the collisionless regime the ion power loss exceeds the calculated neoclassical conduction loss by up to an order of magnitude. Scaling laws are derived for the ion temperature in both ohmically and injection heated discharges.

Machine	Ref	Z_{eff}	R (m)	a (m)	B_ϕ (T)	I_G (kA)	$\bar{n}_e$ ($\times 10^{19} m^{-3}$)	T_e (eV)	T_i (eV)	A_i (mu)	A_f (mu)	E_f (keV)	P_{NI} (MW)	q	#
T11	(9)	~ 1	0.7	0.2	0.875	100	5	550	510	2	1	22	0.6	2.5	1
ISX-B	(10)		0.93	0.27	1.3	190	6.5	1750	1600	2	1	32	1.65	2.7	2
PDX	(11)	~ 1	1.4	0.38	1.7	310	3.2	1000	800	2	1	50	1.0	2.82	3
ISX-B	(12)	0.9	0.93	0.27	1.15	114	2.6	1500	900	2	1	40	0.6	3.95	4
		2.0	0.93	0.27	1.15	104	3.6	1100	650	2	1	40	0.7	4.33	5
		1.3	0.93	0.27	1.15	111	5.2	1000	850	2	1	40	0.6	4.06	6
		2.9	0.93	0.27	1.15	112	5.0	1400	950	2	1	40	0.9	4.02	7
		2.3	0.93	0.27	1.15	142	3.0	1500	1300	2	1	40	1.1	3.17	8
DITE	(4)	4.9	1.17	0.26	2.0	150	1.6	520	900	1	1	30	0.8	3.85	9
PLT	(13,14)	3.5	1.3	0.4	3.2	380-450	2.7	4000	6500	1	2	40	2.4	5.1-4.3	10
		4.5	1.3	0.4	3.2	380-450	4.3	2700	2100	2	1	40	1.2	5.1-4.3	11
T11	(15)	1	0.7	0.2	0.875	100	1.4	530	400	2	2	32	0.32	2.5	12
		1	0.7	0.2	0.78	80	5	580	-	1	2	32	0.32	2.8	13
DITE	(6)	1.4	1.17	0.26	2.0	170	4.6	1200	390	2	1	24	0.8	3.4	14
		1.12	1.17	0.26	2.2	100	2.1	800	660	2	1	24	1.1	6.4	15
		2.03	1.17	0.26	1.35	160	4.4	720	550	2	1	24	0.62	2.4	16
		1.0	1.17	0.26	1.35	110	4.7	800	410	2	1	24	0.68	3.5	17
		1.56	1.17	0.26	2.0	150	3.5	1030	590	2	1	24	1.0	3.85	18
PDX	(16)	~ 3	1.43	0.44	2.4	500	3.2	2500	6000	1	2	50	6.2	3	19
		~ 3	1.43	0.44	1.4	300	3.2	1500	3500	1	2	50	6.2	3	20

REFERENCES

1. W. Pfeiffer and R.E. Waltz, Nuclear Fusion, 19, (1979), 51.
2. L.A. Artsimovich, Nuclear Fusion, 12, (1972), 215.
3. J. Hugill and J. Sheffield, Nuclear Fusion, 18, (1978), 15.
4. R.D. Gill et. al., Proc. 9th Euro. Conf. on Contr. Fusion and Plas. Phys., (Oxford), 2, (1979), 151.
5. R.D. Gill et. al., Proc. 8th Euro. Conf. on Contr. Fusion and Plas. Phys. (Prague,), 1, (1977), 171.
6. R.D. Gill, G.D. Kerbel and A.A. Mirin, to be published.
7. F.L. Hinton and R.D. Hazeltine, Rev. Mod. Phys., 48, (1976), 239.
8. L.A. Berry, Symp. on Plas. Heat. in Tor. Devices, (Varenna, 1974), p151, Editrice Compositori, Bologna.
9. V.M. Leonov, et. al., Plas. Phys. and Contr. Nucl. Fusion Research, 1980, (Brussels), 1, (1981), 393. IAEA, Vienna.
10. M. Murakami et. al., Plas. Phys. and Contr. Nucl. Fusion Research, 1980, (Brussels), 1, (1981), 377. IAEA, Vienna.
11. D. Meade et. al., Plas. Phys. and Cont. Nucl. Fusion Research, 1980, (Brussels), 1, (1981) 665. IAEA, Vienna.
12. D.W. Swain et. al., Proc. 9th Euro. Conf. on Contr. Fusion and Plas. Phys., (Oxford, 1979), Contrib. paper B2.2., 2, (1979), 44.
13. H. Eubank et. al., Plas. Phys. and Contr. Nucl. Fusion Research, 1978, (Innsbruck), 1, (1979), 167. IAEA, Vienna.
14. H. Eubank et. al., Phys. Rev. Lett., 43, (1979), 270.
15. V.S. Vlasenkov, et. al., Plas. Phys. and Contr. Nucl. Fusion Research, 1978, (Innsbruck), 1, (1979), 211. IAEA, Vienna.
16. Private communication from K. Bol.
17. Private communication from M. Murakami.
18. P.E. Stott, Plasma Physics, 18, (1976), 251.
19. F.L. Hinton and M.N. Rosenbluth, Phys. Fluids, 16, (1973), 836.
20. A.A. Galeev and R.Z. Sagdeev, JETP, 26, (1968), 233.

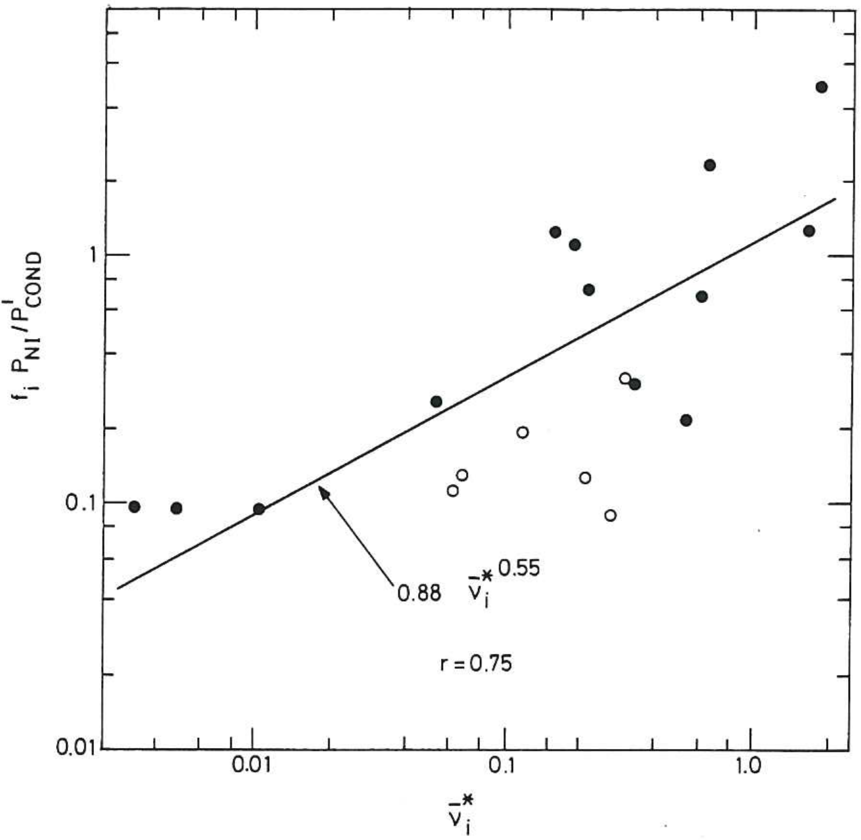

Fig.1 Plot of $f_i\ P_{NI}/P^i_{COND}$ versus $\bar{\nu}_i^*$ for the data of Table 1. Points from ISX–B are plotted as open circles.

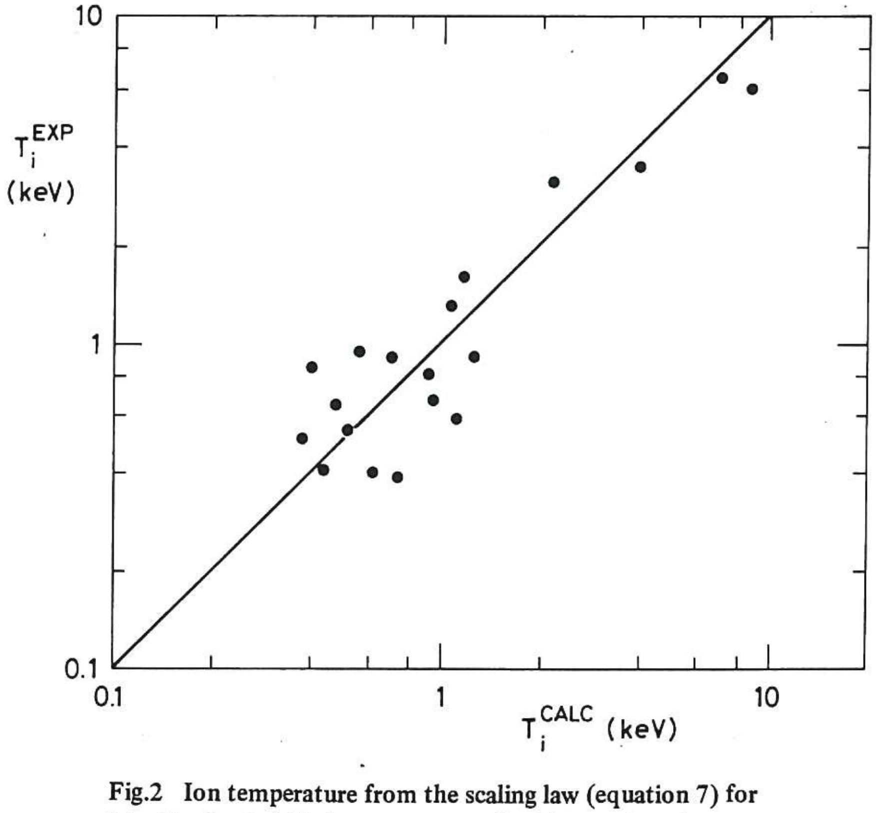

Fig.2 Ion temperature from the scaling law (equation 7) for injection heated discharges compared with experiment.

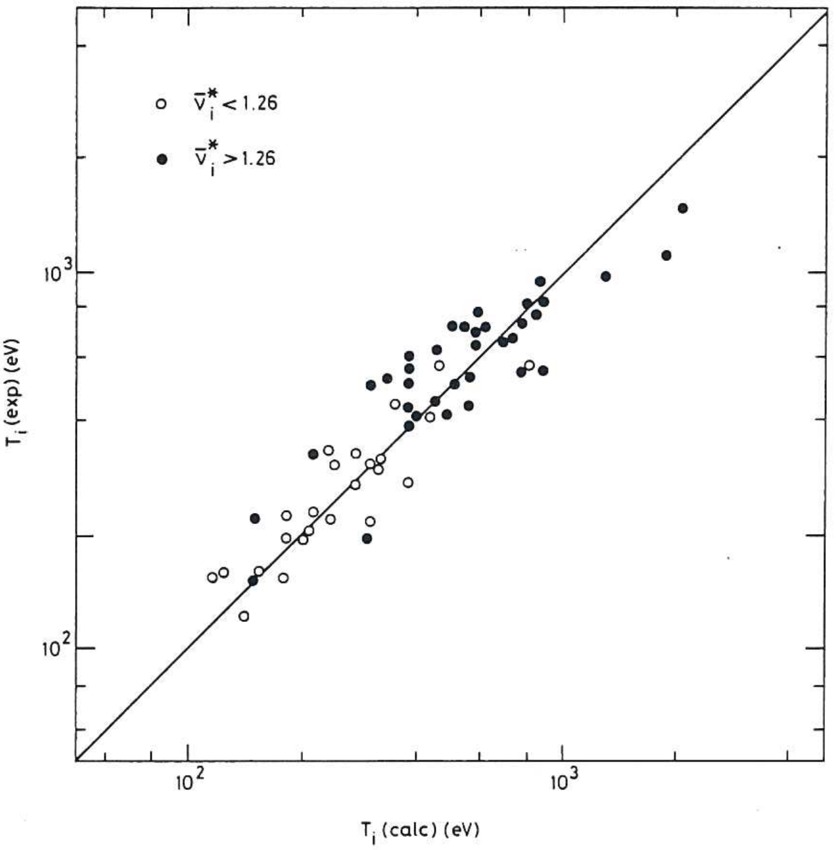

Fig.3 Ion temperature from the scaling law for ohmically heated discharges (equation 8) compared with experiment. High and low collisionality data are indicated separately.

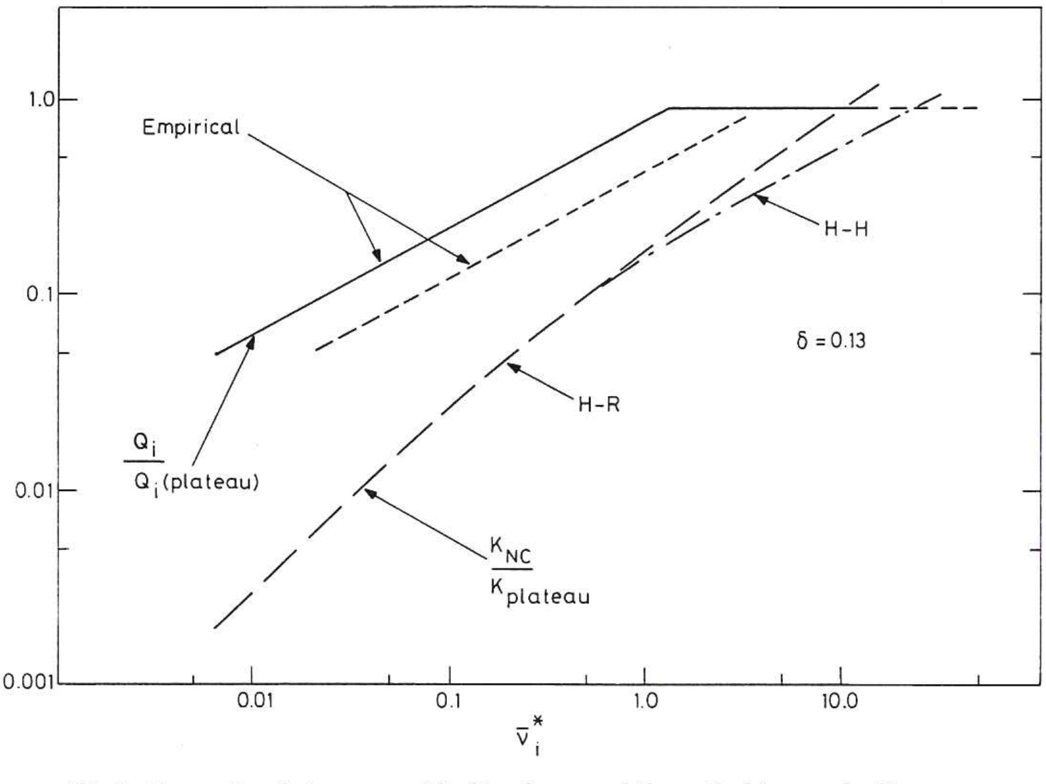

Fig.4 Comparison between empirical ion losses and theoretical ion conduction coefficients calculated from neo-classical theory ((H–H[7]); (H–R[19])). The empirical ion losses with enhanced collision frequency are shown by the broken line.