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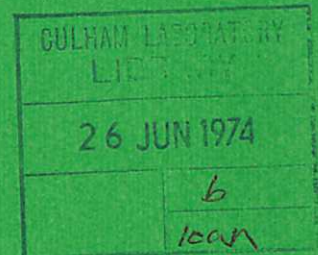
INJECTION OF A NEUTRAL PARTICLE BEAM INTO A TOKAMAK

Experiment and theory

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INTRODUCTION

For a tokamak reactor to approach thermonuclear conditions, a means of heating will have to be found to augment the classical resistive process. One approach is to inject a powerful neutral atomic beam. The neutral particles are ionised within the plasma by charge exchange and are then trapped by the magnetic fields of the tokamak [1]. As the fast ions orbit the toroidal plasma, they transfer energy to the plasma by collisions.

We have tested this approach on the CLEO-TOKAMAK [2] experiment, shown schematically in Fig. 1. It has toroidal field $B_\phi = 2.0$ T, major radius $R_0 = 0.9$ m, plasma minor radius $a_0 = 0.18$ m. The plasma parameters at the time of injection are typically: $V = \pm 3.5$ volts/turn, gas current $I_g = 60$ kA, pulse length 100 ms, mean electron density $\bar{n}_e \sim 1.5 \times 10^{19} \text{ m}^{-3}$, mean conductivity temperature $\bar{T}_0 \sim 80$ eV, central electron temperature from photon scattering $T_{e0} \sim 230$ eV, $Z_{\text{eff}} \sim 7$, central ion temperature from charge exchange neutrals $T_{i0} \sim 200$ eV, mean temperature from plasma diamagnetism ($\beta_\theta \sim 0.4$) $T_d \sim 300$ eV, and neutral atom density (away from the limiter) from

absolute H_β emission $n_n \sim 1.6 \times 10^{15} \text{ m}^{-3}$.

The beam of neutral particles is injected along a tangent to $R = 0.79 \text{ m}$ in a 25 ms pulse at peak current. Injection both parallel and anti-parallel to the toroidal current was achieved by reversing the current. With injection of hydrogen atoms the beam power reaching the plasma is typically 50 kW (maximum 80 kW) of which about 30 kW can be associated with ions on contained orbits for both current directions. These ions consist of about 0.75 A at \mathcal{E}_0 , $\mathcal{E}_0/2$, $\mathcal{E}_0/3$ where $\mathcal{E}_0 = 22.5 \text{ keV}$, the injector energy. In the region of trapping the injected particles make an angle to B_ϕ which is $\theta_p = 25 \pm 25^\circ$ for injection parallel to I_g and $\theta_a = 15 \pm 15^\circ$ for anti-parallel. We have also injected neutral helium atoms which should rapidly ionize to He^{++} at $\mathcal{E}_0 = 26 \text{ keV}$. For this case 20 kW is associated with contained ions.

GROSS CHARACTERISTICS WITH INJECTION

The tokamak plasma is not appreciably disturbed by neutral beam powers up to 50 kW (25% of the ohmic power). The electron density increase produced by injection is up to 10% and this is only twice the number of electrons resulting from ionisation of the beam. Apart from changes of the ion energy spectrum (see later), we observe no other effects of the injection. The conductivity temperature (T_σ) and the diamagnetic temperature (T_d), are measured as functions of time and show no observable changes (i.e. $\leq 5\%$) at the time of injection.

For neutral beam powers between 50 - 80 kW the above density change increases non-linearly with beam power (doubling the density for 80 kW). This effect is attributed to beam-wall interaction.

The transfer of beam momentum to the plasma should produce rotation (v_ϕ) and a change of apparent frequency of M.H.D. oscillations

present in the plasma, assuming no simultaneous compensating change in minor azimuthal velocity. The absence of any observable change of frequency on injection sets a limit $V_\varphi < 6 \times 10^3 \text{ ms}^{-1}$ (2% of the sound speed). If this represents solid body rather than surface rotation, then for the known injected momentum we deduce a momentum containment time $\tau_m \leq 3 \text{ ms}$.

SPECTRA OF CONTAINED HIGH ENERGY IONS

The slowing down of the contained hydrogen ions is clearly reflected in the continuous energy spectrum which rapidly develops from the three discrete peaks at the injection energies. This spectrum is measured in the energy range $\mathcal{E} = 4$ to 30 keV through the charge-exchange neutrals emitted along a tangent to $R = 0.92 \text{ m}$ with acceptance angle 0 to 20° to B_φ . The count rate, $N(\mathcal{E})$, from the neutral particle energy analyser with channel width $\Delta\mathcal{E}/\mathcal{E} = 3\%$, are corrected for charge-exchange efficiency in the plasma and detector efficiency before being plotted (Fig. 2) in the form $G(\mathcal{E}) = \mathcal{E}^{-\frac{1}{2}} N(\mathcal{E})/\Delta\mathcal{E}$.

The collisional interaction of the contained ions with the plasma is described by the Fokker-Planck equation [3] for the velocity distribution function f . (The right hand side terms represent respectively: friction, angular scattering, velocity diffusion, electric acceleration, charge-exchange and the source):

$$\begin{aligned} \frac{\partial f}{\partial t} = & \frac{1}{\tau_s} \left[\frac{1}{v^2} \frac{\partial}{\partial v} \{ (v_c^3 + v^3) f \} + \frac{m_i Z_{\text{eff}} v_c^3}{2m_b \bar{Z} v^3} \frac{\partial}{\partial \zeta} \{ (1 - \zeta^2) \frac{\partial f}{\partial \zeta} \} \right. \\ & + \frac{Dm_e v_e^2}{2m_b v^2} \frac{\partial^2}{\partial v^2} (v^2 f) \left. - \frac{Z_b e E^*}{m_b} \left[\frac{(1 - \zeta^2)}{v} \frac{\partial f}{\partial \zeta} + \zeta \frac{\partial f}{\partial v} \right] \right. \\ & \left. - f/\tau_{cx} + S(\zeta, t) \delta(v - v_0) \right] \end{aligned}$$

where m_i and m_b are plasma and injected ion masses, $v = (2\mathcal{E}/m_b)^{1/2}$, $v_e = (2kT_e/m_e)^{1/2}$, $v_c = (3\sqrt{\pi} \bar{Z}/4)^{1/3} (m_e/m_i)^{1/3} v_e$, $Z_{eff} = \sum n_j Z_j^2 / n_e$, $\bar{Z} = \sum Z_j^2 n_j m_i / n_e m_j$, $\tau_s = 1.25 \times 10^{18} n_e^{-1} A_b Z_b^{-2} [T_e \text{ (keV)}]^{3/2}$; $E^* = [1 - 1/Z_{eff}] V/2\pi R_0$, $\zeta = v_{||}/v$, and subscript b refers to injected beam particles. V is positive or negative for injection parallel or anti-parallel with I_g . The above $G(\mathcal{E})$ is the integral of f over the angles ζ as seen by the detector. The value of \bar{Z} is in the range 0.5 to 1.0 and for typical tokamak conditions [4] $\bar{Z} = 0.9 \sim 1.0$. In deriving the above equation we have assumed that the plasma behaves classically (e.g. classical resistance) and consequently $\bar{T}_e = [0.58 Z_{eff}/\gamma_E (Z_{eff})^{5/2}] T_0$ where $\gamma_E (Z_{eff})$ is given by Spitzer and Harm [5]. If the resistance is enhanced above classical then Z_{eff} in E^* must be increased by the enhancement (anomaly) factor.

The equation allows velocity diffusion to $v > v_0$ due to collisions with electrons. Additional diffusion due to collisions between injected ions is included through the diffusion enhancement factor D .

For $Z_{eff} > 1$ in E^* , the effect of the electric field is to accelerate or retard the ions and consequently shift the spectrum to high or lower energies for injection parallel or anti-parallel with the plasma current, respectively. The relative extent of the spectrum with $\mathcal{E} > \mathcal{E}_0$ for these two cases is therefore different and depends only on E^* and τ_s , but not on the velocity diffusion term.

By linearizing the equation about \mathcal{E}_0 and averaging over angles we have obtained [2] a simple analytical solution for the steady state f and hence $G(\mathcal{E})$ and compared this with the measured spectrum at peak signal (6 ms after injection) as described below.

- 1) The measured relative extents of upward velocity diffusion

for parallel and anti-parallel injection together with the accurately known values of \mathcal{E}_0 , V , $\bar{\zeta}$ and \bar{n}_e yield a value for $\tau_s (1 - 1/Z_{\text{eff}})$ which is a function of \bar{T}_e and Z_{eff} .

2) Combining this with the accurately known \bar{T}_0 , which is also a function of \bar{T}_e and Z_{eff} , we obtain $\bar{T}_e = 280$ eV ($\tau_s = 12$ ms) and $Z_{\text{eff}} \sim 6.7$ which are consistent with other direct estimates.

3) We use the measured upwards velocity diffusion with the above \bar{T}_e and Z_{eff} to obtain the value $D = 4$ for the diffusion enhancement factor. This factor could be explained by collisions between injected ions if their density reaches $n_b \sim 10^{18} \text{ m}^{-3}$. This is possible for an effective beam radius $r \leq 70$ mm and containment time $\tau \geq 5$ ms.

4) For energies immediately below \mathcal{E}_0 we obtain agreement between experiment and theory based on the above \bar{T}_e , Z_{eff} and D , without involving loss by charge exchange. This implies a charge-exchange time $\tau_{\text{cx}} > \tau_s/3$ and corresponding $n_0 < 2.0 \times 10^{15} \text{ m}^{-3}$.

By similar linearization and averaging we have obtained a simple analytical solution for the time dependent f . Substituting the above values for \bar{T}_e , Z_{eff} and D , these solutions agree well with the measured time dependent signals, both above and below \mathcal{E}_0 , but only up to peak signal. After this the measured signals decrease and this is not understood.

The solution of the complete equation has been computed [3] for the above values of \bar{T}_e , Z_{eff} , D and $\bar{n}_n = 0.75 \times 10^{15} \text{ m}^{-3}$. This solution is plotted in Fig. 2 for comparison with experiment and is used to derive both the perpendicular energy spectrum of injected ions and the transfer of power to the electrons and to the ions of the plasma.

DISTORTION OF THE THERMAL ION SPECTRUM BY INJECTION

We measure the perpendicular (to B_ϕ) ion energy spectrum ($0.2 < \mathcal{E} < 5.4$ keV) in the presence and absence of the neutral beam. For this we use a calibrated charge exchange neutral particle energy analyser with six channels, which takes a 15 msec sample every 20 msec. The measured spectra, corrected for the charge-exchange efficiency in the plasma and detector efficiency, are shown in Fig. 3 for parallel injection. (Note a Maxwellian distribution would appear linear). These curves are normalised at $\mathcal{E} = 500$ eV for comparison because injection increases the absolute signal by about a factor of two. In the absence of the injected beam we obtain the usual two temperature spectrum, yielding a central temperature $T_{i0} = 198 \pm 8$ eV. In the presence of hydrogen injection we observe a substantial high energy ($\mathcal{E} > 1.5$ keV) tail on the thermal spectrum. We interpret this tail as being predominantly the slowed down hydrogen ions which have been scattered into the perpendicular direction. The computed perpendicular spectrum has an energy dependence which is critically dependent on Z_{eff} . Assuming that all the ions observed at $\mathcal{E} = 5.4$ keV are from injection, the measured dependence on \mathcal{E} corresponds with $Z_{\text{eff}} \sim 4$ in moderate accord with other estimates.

To test this interpretation we need to distinguish between injected and plasma ions. This we did by injecting helium atoms into a hydrogen plasma and using the estimated 50 to 1 discrimination of the detecting system against helium with respect to hydrogen. As can be seen in Fig. 3 there remains a substantial tail. Analysis of the helium beam showed that despite considerable conditioning with helium the walls still contained sufficient hydrogen to contaminate the beam. However the observed tail could not all be explained by the measured

hydrogen ($\leq 20\%$) in the helium beam. Clearly with helium injection, the enhancement of the thermal tail is not solely due to slowed down injected ions.

Cordey [6] has since shown that the presence of the fast injected ions increases the upward velocity diffusion of the thermal plasma ions. This effect produces a departure from the maxwellian distribution in the form of a high energy tail which is appreciable for $\mathcal{E} > \mathcal{E}_s$ where $\mathcal{E}_s = (n_i/n_b)^{2/5} \mathcal{E}_t^{1/5} (T_i/Z_b)^{4/5} = 1.5 \text{ keV}$ for the injection of helium in this experiment (n_b = beam ion density, $\mathcal{E}_t = \frac{1}{2} m_i v_c^2$). For the injection of helium ions ($Z_b = 2$) the effect is very marked and the calculated enhancement is a third of that observed. For the injection of hydrogen \mathcal{E}_s is up by a factor $2^{4/5} = 1.8$ so that $G(\mathcal{E})$ is down by more than two orders of magnitude at \mathcal{E}_s and the effect should be negligible.

HEATING OF PLASMA IONS BY INJECTION

We consider the rise in average ion energy (ΔW_i), produced by injection, in two parts (i) the effective rise of ion temperature ΔT_i from the Maxwellian part of the spectrum (0.5 to 1.5 keV) and (ii) the additional average isotropic energy per ion contributed by the distorted tail.

The measured values in the absence of injection (off) and during parallel injection (on) are given in Table I with statistical errors. The error in ΔT_i is obtained from the statistical combination of errors. However we illustrate this accuracy in Fig. 4 by plotting $\log G_{\text{on}} - \log G_{\text{off}} \propto (\Delta T/T_{\text{on}} T_{\text{off}}) \mathcal{E}$. Strictly these estimates should be made after subtracting the contribution in this region from the slowed down injected ions, and this is tabulated as $\Delta T_{i0}'/T_{i0}$.

Adding the contribution to ΔW_i from integrating the tail itself, we arrive at the tabulated $\Delta W_i/W_i$.

TABLE I

	$(T_{io})_{off}$	$(T_{io})_{on}$	$\Delta T_{io}/T_{io}$	$\Delta T_i/T_{io}$	$\Delta W_i/W_i$
Hydrogen	198 ± 8	225 ± 9	$14 \pm 6\%$	9%	19%
Helium	185 ± 9	208 ± 9	$12 \pm 6\%$	-	-

The heating of the two species, electrons and ions, (ΔT_s) can be calculated from the beam energy input P_{Ns} to each species calculated as above from the Fokker-Planck equation. We assume that the species are effectively decoupled and have a known dependence of loss rate on temperature, $P_{Ls} \propto T^{\alpha_s}$, ($\alpha_e = 0.5$, neoclassical scaling, $\alpha_i = 2.5$ plateau regime). The power balance equations then yield [1] $\Delta T_s/T_s = (\alpha_s - \beta_s)^{-1} (P_{Ns}/P_{Js})$ where $P_{Js} \propto T^{\beta_s}$ is the ohmic power input ($\beta_e = -1.5$, $\beta_i = -0.5$). The computed power deposition for hydrogen injection, $P_{Ne} = 20$ kW, $P_{Ni} = 10$ kW, leads to $\Delta T_e/T_e \sim 6\%$, $\Delta T_i/T_i \sim 12\%$, while for helium injection $P_{Ni} \sim 12$ kW, $P_{Ne} \sim 8$ kW leads to $\Delta T_e/T_e \sim 2\%$, $\Delta T_i/T_i \sim 13\%$. These are in good agreement with observations.

CONCLUSION

For injected powers up to 25% of the resistive power, we find (i) no appreciable disturbance of the plasma or heating of the electrons ($\leq 5\%$), (ii) classical loss of energy from the beam (i.e. slowing) (iii) the expected ($\sim 10\%$) increase in ion energy (iv) a distortion of the plasma ion spectrum.

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We also wish to mention the simultaneous but independent work on neutral injection at Princeton [7].

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NEUTRAL INJECTOR

LOW ENERGY DETECTOR

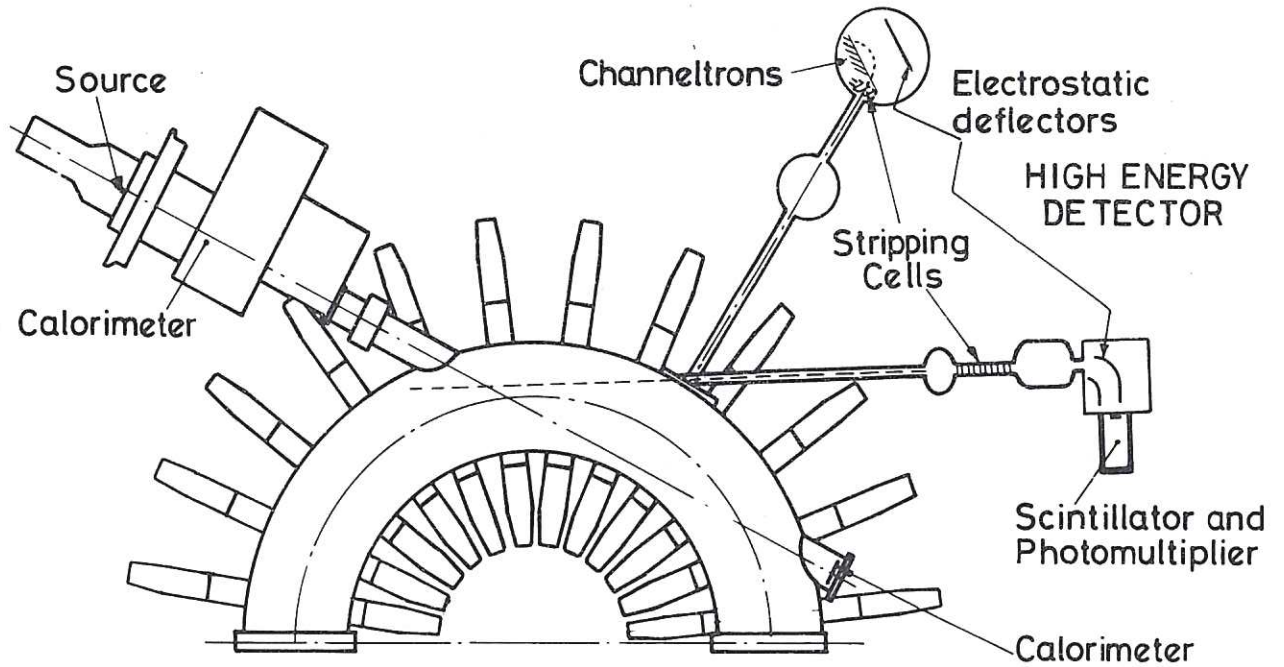


Fig. 1. Schematic of experiment.

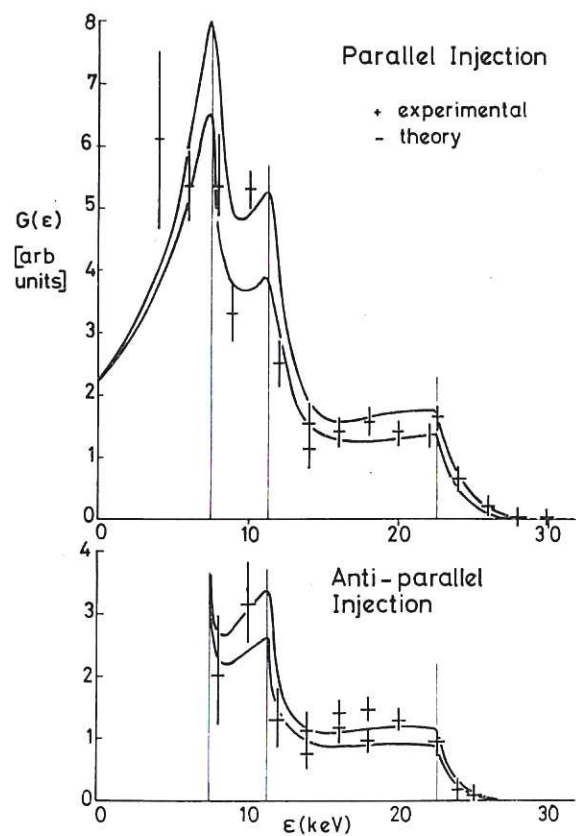


Fig. 2. Spectra of contained high energy ions; experiment and theory for detecting angles 0° (top curve) and 20° (lower curve).

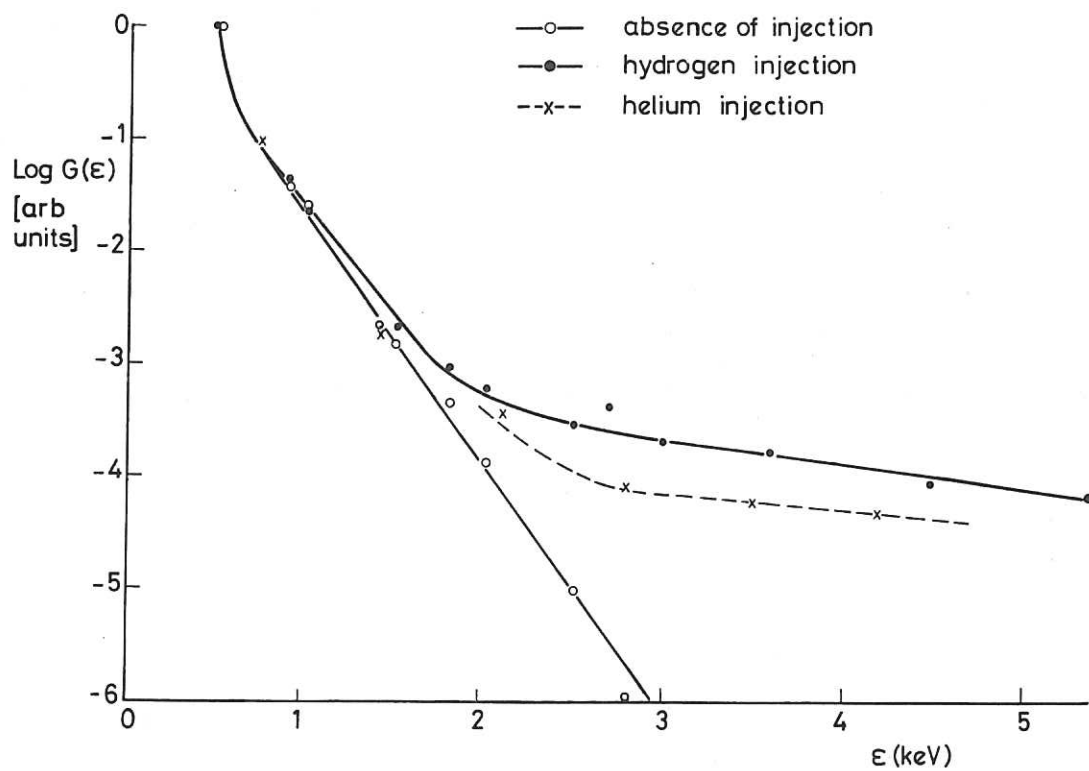


Fig. 3. Perpendicular ion energy spectra.

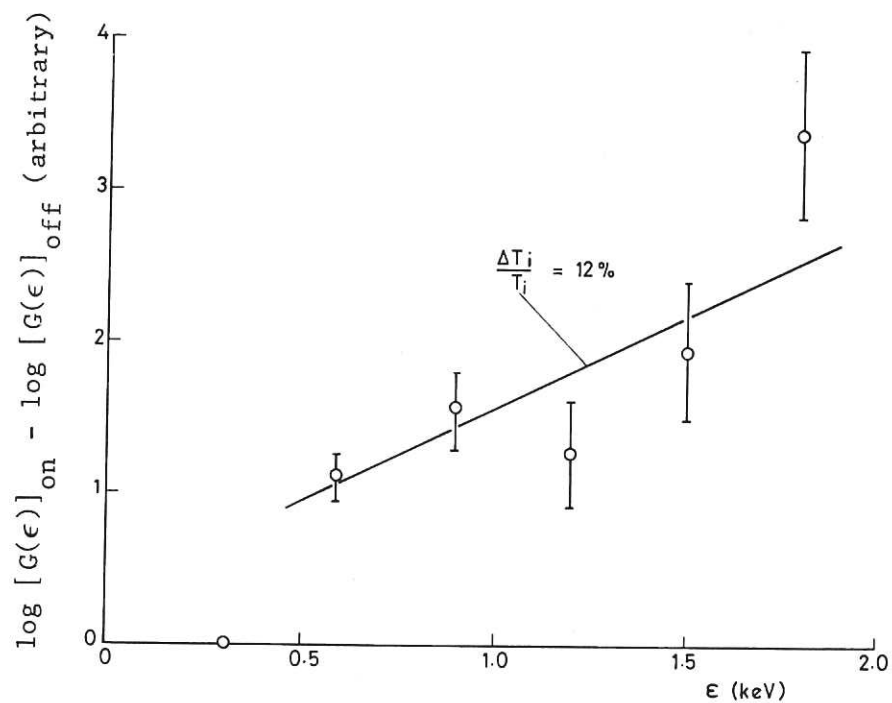


Fig. 4. Difference between $G(\epsilon)$ with and $G(\epsilon)$ without helium injection; demonstration of positive ΔT_i from gradient. Normalized at 0.3 keV.

