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F. Ryter[1], C. Angioni[1], C. Giroud[2], A.G. Peeters[3], T. Biewer4, R. Bilato[1], J. Candy[5], E. Joffrin[6], T. Johnson[2], H. Leggate[2], E. Lerche[7], G. Madison[2], P. Mantica[8], D. Van Eester[7], I. Voitsekhovitch[2], R.E. Waltz[5] and JET Contributors*

JET-EFDA, Culham Science Centre, OX14 3DB, Abingdon, UK

[1]Max-Planck-Institut f¨ur Plasmaphysik, EURATOM Association, D-85748 Garching
[2]Culham Science Centre, EURATOM/UKAEA Association, OX14 3DB, Abingdon,UK
[3]Centre for Fusion Space and Astrophysics, University of Warwick, Coventry 7AL, UK
[4]Fusion Energy Division, Oak Ridge National Lab., P.O. Box 2008 MS 6169 Oak Ridge, USA
[5]General Atomics, San Diego, CA 92186, USA
[6]JET-EFDA-CSU, Culham Science Centre, OX14 3DB, Abingdon, UK
[7]LPP-ERM/KMS, Association Euratom-Belgian State, TEC, B-1000 Brussels, Belgium
[8]Istituto di Fisica del Plasma, EURATOM/ENEA-CNR Association, 20125, Milano, Italy
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ABSTRACT.

In fusion plasmas, turbulence-driven heat transport generally dominates both electrons and ions channels. It increases above a threshold in normalized gradient with a rate named stiffness. Heating power modulation experiments provide a direct measurement of the stiffness, as already demonstrated for the electrons, but not for ions so far. In this paper, we report, for the first time, results yielding the ion stiffness deduced from modulation experiments. The experiments were carried out in JET plasmas using Ion Cyclotron Resonance Heating in the 3He scheme. The ion stiffness is larger than that of electrons, but remains moderate and is in agreement with the values yielded by non-linear gyro-kinetic calculations. As a fraction of the electron heating is also modulated in these experiments, a comprehensive analysis of both ion and electron heat transport can be carried out simultaneously, together with an experimental assessment of the ICRH heat sources of the ^{3}He scheme.

1. INTRODUCTION

In fusion plasmas, turbulent phenomena driven by the Ion Temperature Gradient and Trapped Electron Mode instabilities in general dominate ion and electron heat transport, respectively. The ITG and TEM modes are unstable above respective thresholds in normalized temperature gradients, $R\nabla T/T = R/L_T$, leading to an increase of transport above the threshold. The rate with which transport increases above the threshold is called "stiffness", characterized by a factor cs which will be defined below. The observed resilience of the temperature profile shape to changes in heating power deposition, see e.g. [1, 2, 3, 4, 5, 6, 7, 8], can be explained by these properties [9]. For the electrons, the existence of both threshold and stiffness have been directly evidenced experimentally in several devices [10, 11, 12, 13], but only very recently for ions [14]. "Perturbative" transport experiments, in which the temperature perturbation induced by modulating the heating power is analyzed, yields the stiffness properties. Indeed, the propagation of the excited heat pulses is determined by the slope of the heat flux with respect to the temperature gradient, yielding the heat pulse diffusivity [15, 16]:

$$\chi_j^{HP} = -\frac{\partial q_j}{\partial n_j \nabla T_j} = \chi_j^{PB} + \frac{\partial \chi_j}{\partial \nabla T_j} \nabla T_j \qquad (1)$$

where the subscript j denotes e or i (electron or ion), q heat flux and n density, whereas χ_j^{PB} is the usual heat diffusivity from power balance. In the experiments, χ_j^{HP} is derived from the Fourier transform of the temperature data, interpreted in slab geometry [16]. This yields 2 estimates for the heat pulse diffusivity, $\chi_j^{Amp} \propto (\delta \mathrm{Ln}(Amp) = \delta r)^{-2}$ derived from the amplitude profile and $\chi_j^{phi} \propto (\delta\phi = \delta r)^{-2}$ from the phase profile. Due to damping processes, which affect amplitude and phase profiles, these 2 quantities differ at low modulation frequencies ($\chi_j^{phi} \geq \chi_j^{Amp}$), but converge asymptotically towards χ_j^{HP} at high modulation frequencies for which damping becomes negligible. However, in the geometric mean, $\sqrt{\chi_j^{Amp} \geq \chi_j^{phi}}$, the damping effects mathematically cancel and, at any frequency, it can be considered as a good experimental estimator of the actual value of χ_j^{HP}.

The modulation method has been extensively used to investigate electron heat transport properties, [17, 9, 18], but not applied to the ions so far. The main goal of the work presented here was to modulate the ion temperature and deduce experimentally, for the first time, the stiffness of ion transport. As a fraction of the electron heating power was also modulated, these experiments allow a comprehensive and simultaneous investigation of both ion and electron heat transport by perturbative methods.

2 EXPERIMENTS

2.1 EXPERIMENTAL CONDITIONS

The experiments presented here have been carried out in the JET tokamak, $R \approx 3$m and a $\approx$1m, at a rather high edge safety factor value, $q_{95} \approx 6$ to avoid sawteeth. They were run in deuterium L-modes at a density of about $3\,10^{19}\,\mathrm{m}^{-3}$, heated by Neutral Beam Injection as background heating and Ion Cyclotron Resonance Heating in the ^{3}He minority scheme for the power modulation part. The RF power was modulated at f_{mod} with a 50/50 duty-cycle and a modulation amplitude of about 80%. JET offers a unique opportunity for localized ion and electron heating by ICRH in the 3He minority scheme, whose heating properties depend on the ^{3}He concentration [^{3}He]. For [^{3}He] $\approx$ 8%, there is a maximum of ion heating from the ICRH-accelerated ions which deliver a dominant fraction of their energy to the plasma as ion heating, significantly more than in the hydrogen minority scheme. The power deposition is calculated by the time-dependent PION code [19], yielding the ICRF heat sources for analyses and transport simulations. We also get ICRH power deposition profiles from the SELFO code which is not time-dependent but provides a more accurate distribution of the power in the different channels.

The essential measurement of the ion temperature is provided by the CXRS diagnostic. The experiments have been carried in three distinct series of discharges, in 2002, 2003 and 2006. In the 2002 and 2003 campaigns, the time resolution of the T_i measurement was 50ms which limited the maximum modulation frequency to about 4Hz. The 2002 discharges demonstrated that it was possible and meaningful to address ion perturbative transport with this scenario. In the 2003 series, we varied the NBI heating to investigated the possible influence of T_i. These 2 series yielded good results, which however required validation by experiments at higher modulation frequencies. This was finally possible in the 2006 campaign for which the CXRS diagnostic had been updated, providing 2 separate measurements (CXFMand CXGM) each with a time resolution of 10ms. We obtained good modulation data from an ICRH modulation frequency scan $4 \le f_{mod} \le 20$Hz. As these discharges were carried out at the very beginning of the experimental campaign, due some unfortunate technical difficulties, the data from the third core CXRS and edge CXSR diagnostics turned out to be incorrect. As shown below, not only the modulation of T_i but also that of T_e are analyzed in these experiments. The T_e measurement is provided by the Electron Cyclotron Emission radiometer diagnostic.

2.2 ANALYSIS OF THE MODULATED TI DATA

The analysis of the T_e modulation by Fourier transform is a widely used method in transient transport

studies. The high time resolution of the ECE diagnostic does not limit the modulation frequency and its high sensitivity provides in general data with a very good signal-to-noise ratio.

The situation for T_i is different: the time resolution of the CXRS data can limit the highest modulation frequency. This was the case for the 2002 and 2003 series with the 50ms time resolution. The 10ms exposure time available for 2006 provided much better conditions and room for optimizing the signal-tonoise ratio. The best S/N is a compromise between the integration time on which the T_i analysis is carried out and the number of measurement points available for the Fourier transform. In our experiments, several CXRS exposure frames with 10ms integration time can be grouped prior to the T_i analysis. At low modulation frequency, up to 5 frames can be grouped without affecting the phase. This demonstrates the validity of the 2002 and 2003 data with 50ms resolution at 4Hz. With 10ms exposure time, the quality of the modulated T_i data is good under our experimental conditions and the best S/N is obtained when grouping at most 2 or 3 frames, depending on the cases. Thus, for 2006, the availability of two independent CXRS systems and the possibility of grouping the frames provides an excellent set of data to investigate the heat pulse propagation in the frequency scan.

The perturbative transport results of the frequency scan, represented by χ_i^{phi}, χ_i^{Amp} and χ_i^{HP} versus f_{mod} analyzed at about mid-radius ($R \approx 3.4$m), are plotted in the left plot of Fig.1. The values are the mean of all the realistic fits which can be made using the available data for each frequency, whereas the error bars are provided by the corresponding standard deviation. As predicted, $\chi_i^{phi} > \chi_i^{Amp}$ and these quantities converge towards χ_i^{HP} as f_{mod} increases. The value of χ_i^{HP} is close to $2\text{m}^2/\text{s}$ and does not depend on f_{mod}. This frequency scan indicates, for the first time, that ion perturbative transport behaves as expected. Therefore, we conclude that this method can be used to investigate the properties of ion heat transport. This frequency scan also indicates that the data at f_{mod} = 4 Hz, obtained in the 2002 and 2003 series are valid. This is due to the fact that the ion stiffness is not very high, as shown below. Indeed, measuring higher stiffness requires higher modulation frequency to catch the propagation of the heat pulses correctly. In the right plot of Fig. 1, we illustrate the results from the heating power scan of 2002 and 2003 by plotting χ_i^{PB} and χ_i^{HP} normalized by the gyro-Bohm dependence $T_i^{3/2}$ versus T_i. As indicates by the x-axis, the scan provides a significant variation in T_i. Within the error bars, these normalized diffusivities do not vary with heating power, as indicated by the absence of dependence on T_i. This demonstrates that the basic characteristics of ion transport do not change significantly in this power scan, also supported by the fact that the ratio χ_i^{HP}/χ_i^{PB} remains constant.

3 MODELING

3.1 THE CRITICAL GRADIENT MODEL

Turbulence-driven electron and ion heat transport increases above a threshold in R/L_{Tj} with a given stiffness. An empirical model, taking these properties into account, has been developed for electron heat transport and successfully tested on several devices [20, 21, 9]. This Critical Gradient Model (CGM) describes heat diffusivity with a linear increase above the threshold and can be written in

the same form for the electron and ion channels as:

$$\chi_j = \chi_{j,s}\, q^{3/2}\, \frac{T_j}{eB}\, \frac{\rho_j}{R} \left[\frac{R}{L_{T_j}} - \frac{R}{L_{T_{j,crit}}} \right] H\left(\frac{\rho_j}{R} - \frac{R}{L_{T_{j,crit}}} \right) + \chi_{j,0} \qquad (2)$$

where q is the safety factor, B magnetic field and H is the Heaviside step function which mimics the existence of the threshold. The normalized ion gyro-radius ρ_j is $\rho_s = \sqrt{m_i T_e / eB}$ for the electrons and $\rho_i = \sqrt{m_i T_e / eB}$ for the ions. The stiffness factor is defined as $\chi_{j,s}$ and $R/L_{Tj,crit}$ is the threshold. The term $\chi_{j,0}$, which represents transport below the threshold, is in general negligible as soon as R/L_{Tj} is somewhat above the threshold. This is neo-classical transport for the ions and an arbitrary value for the electrons. The gyro-Bohm factor, $T_j / (eB)\, \rho_j / R \propto T_i^{3/2}$, is commonly used for transport driven by microturbulence. Note that the linear dependence of χ_j versus R/L_{Tj} assumed in this model implies a quadratic dependence of the heat flux. The expression for χ_j^{HP} can be derived explicitly from Eq. 2 yielding:

$$\chi_j^{HP} = \chi_{j,s}\, q^{3/2}\, \frac{T_j}{eB}\, \frac{\rho_j}{R} \left[2\, \frac{R}{L_{T_j}} - \frac{R}{L_{T_{j,crit}}} \right] H\left(\frac{\rho_j}{R} - \frac{R}{L_{T_{j,crit}}} \right) + \chi_{j,0} \qquad (3)$$

3.2 MODULATED HEAT SOURCES BY ICRH

In the ICRH ^{3}He minority scheme, the faster RF-accelerated 3He ions deliver their energy by collisions to the electrons, with a long time constant, whereas the slower ones provide ion heating, with a shorter time constant. The respective power densities are $P_{e,coll}$ and $P_{i,coll}$, peaked around the radial position of the ICRF resonance. In addition, direct electron heating by the fast wave occurs, without any time constant, yielding the centrally peaked deposition $P_{e,direct}$. These processes are calculated by the time-dependent PION code, taking into account the RF power modulation. The time-averaged power deposition profiles for a representative shot of the frequency scan are indicated in Fig.2 left plot. In these discharges, $P_{i,coll}$ and $P_{e,coll}$ are deposited somewhat off-axis, with a maximum at $\rho_{tor} \approx 0.2$, whereas $P_{e,direct}$ is indeed localized on the plasma axis. Due to the time constants of the energy transfer, the modulation amplitudes of $P_{i,coll}$ and $P_{e,coll}$ decrease with *fmod* whereas the phase delay with respect to the RF power increases, Fig.2 right plot. Note the large phase delay of $P_{e,coll}$. The points exhibit some scatter which is due to the shot to shot variation of [3He] and collisionality, as tentatively indicated by the error bars. For such discharges, the heating powers yielded by the SELFO code compared to those of PION are: $\approx 0.8 P_{i,coll}$, $\approx 3.2 P_{e,coll}$ and $0.5 P_{e,direct}$. These differences will be taken into account in the transport simulations.

3.3 NON-LINEAR GYRO-KINETIC CALCULATIONS

Based on the experimental data of the 2006 series, non-linear gyro-kinetic calculations, including collisions, have been carried out with the GYRO code, [22], with the following parameters. The size of the box was $81\rho_s$ and $113\rho_s$ in the x and y direction respectively, 16 toroidal modes in the

$k_y\rho_s$ window 0.056 – 0.836 were included. We investigated, at constant temperature, the dependence of the heat fluxes q_e and q_i upon R/L_{Ti} and R/L_{Te} around the experimental values, R/L_{Ti} = 5, R/L_{Te} = 8.4 and R/L_{ne} = 2. The values of T_e and T_i are comparable, but the profile shapes are quite different yielding the different gradients. We also studied the influence of [^{3}He]. The analysis reveals that heat transport is dominated by the ITG instability in these plasmas. The dependence of q_i and q_e on R/L_{Ti} and R/L_{Te} respectively (diagonal terms), are summarized in Fig.3. Both q_i and q_e increase with their corresponding gradient, but q_i faster than q_e. This is expressed quantitatively by the respective χ_s values deduced from the parabolic fits also plotted in the figure. It should be underlined that $q_i = f(R/L_{Ti})$ is very close to a quadratic dependence whereas $q_e = f(R/L_{Te})$ is close to linear and the parabolic fitting is not particularly appropriate, as also found in plasmas dominated by the TEM instability, [23, 24]. The ion stiffness varies between 1.1 and 1.55, depending on [^{3}He], whereas the electron stiffness 0.15 is much smaller. Therefore, the ions seems to be stiffer than the electrons, but the value of $\chi_{i,s}$ remains moderate and the ions are not extremely stiff, at least in the conditions of our experiments. We noticed in this study that c*i*;*s* increases by about a factor of 2 when R/L_{Te} approaches R/L_{Ti}. The influence of [^{3}He] is illustrated by two assumptions on its profile: flat profile and as peaked as the electron density, both with [^{3}He] = 15%. Two effects contribute: the dilution of the ion density and the induced change in R/L_{ni} . Our study also yields the cross-dependencies (off-diagonal terms) $q_i = f(R/L_{Te})$ and $q_e = f(R/L_{Ti})$, Fig. 4. It shows that *qi* is almost independent of R/L_{Te} in the range of the experiment, whereas *qe* exhibits a strong dependence on R/L_{Ti}, in agreement with the ITG dominated regime. We characterize this effect by $\chi_{e-i;s}$.

3.4 TRANSPORT MODELING

The transport simulations are performed with the ASTRA transport code [25] in which the CGMhas been implemented for both ion and electrons. The simulations are time-dependent using the ICRH heat sources provided by the PION code, corrected by the SELFO information, as specified below. The NBI heating profiles are taken from TRANSP, [26]. The calculated time-dependent T_i and T_e are Fourier-analyzed as those from experiments. The χ_s values from GYRO indicated in Figures 3 and 4 must be divided by $q^{3/2}$ for the CGM used in ASTRA. Restricting to the case with flat [3He] profile this yields the values for the ASTRA simulations: $\chi_{i,s} \approx 0.35$, $\chi_{e,s} \approx 0.05$ and $\chi_{e-i,s} \approx 0.12$, with about 20% variation due to the differences on q between ASTRA ($q \approx 1.8$) and GYRO (q = 2:2). The value of $\chi_{e,s}$ is smaller than found in previous comparisons of the CGM with JET data by at least a factor of 5, [17]. There are two possible reasons for this which are still under investigation. Firstly, as mentioned above, the quadratic dependence of the CGM for q_e does not agree with the GYRO results, leading of course to very different values of χ_s. Secondly, first tests indicates that electron heat transport is better accounted for in GYRO using 32 modes and *kyrs* up to 1.5 instead of 16 modes and $k_y\rho_s \leq 0.84$: q_e is increased. The study will be completed with such time-consuming calculations very soon.

We first compared experiment and simulations for T_i, illustrated in Fig.5 which shows time-

averaged T_i profiles, as well as amplitudes and phases of the modulation for discharges at f_{mod} 8 and 20Hz. The simulations have been carried out with 3 values of $\chi_{i,s}$ around the value yielded by GYRO. The best agreement is achieved close to this value, demonstrating that, under our experimental conditions, the GYRO non-linear simulations describe well the ion heat transport. Taking for $P_{i,coll}$ the 20% higher PION value increases somewhat T_i and amplitude which tends to improve the match.

The modulation of the electron temperature is more complex and the results presented here meant as a discussion and should not be considered as definitive so far. The modulation is excited by two heat sources, $P_{e,coll}$ and $P_{e,direct}$, with different profiles and time constants. In addition, as indicated by the gyro-kinetic calculations, the off-diagonal term induced by R/L_{Ti} should also be included. As mentioned above, the values derived from GYRO, $\chi_{e,s} \approx 0{:}05$ and $\chi_{e-i,s} \approx 0{:}12$, are very low and indeed the simulations made with these values do not fit the data at all. We therefore increased these quantities to obtain an acceptable match with the experiment. The simulations have been carried out with 4 assumptions:

Case a: $\chi_{e,s} = 0.14$, $\chi_{e-i,s} = 0.25$, SELFO powers.

Case b: $\chi_{e,s} = 0.14$, $\chi_{e-i,s} = 0.25$, PION powers.

Case c: $\chi_{e,s} = 0.14$, $\chi_{e-i,s} = 0.25$, SELFO for collisional heating but the larger PION power for $P_{e,direct}$.

Case d: $\chi_{e,s} = 0.35$, $\chi_{e-i,s} = 0$, SELFO powers.

The experimental profiles of T_e, amplitude and phase of the modulation for 8Hz and 20Hz are shown in Fig.6, together with modeling using the same coefficients for both frequencies. We adjusted $\chi_{e,s}$ and $\chi_{e-i,s}$ such that the T_e profiles match the experiment, as shown on the left plots. We first focus on the 8Hz case. The middle box indicates that the experimental amplitude does not exhibit any particular feature, except an increase toward the edge which is attributed to a spurious modulation of density excited at the very edge by the RF power and which also reduces the phase there. The modulation amplitude is well reproduced by case χ (SELFO with more central direct heating) and very poorly by case b for which the PION $P_{e,coll}$ is clearly to low. The experimental phase exhibits an unusual non-monotonic behaviour at about $R = 3.5$m, which can only be caused by a source-like term with small phase delay. It cannot be caused by fast 3He ions because their phase delay is by far too large. This phase behaviour can be tentatively explained by the three main elements contributing to electron heat transport, $P_{e,direct}$, $P_{e,coll}$ and $\chi_{e-i,s}$, as follows. The centrally deposited heating power $P_{e,direct}$ excites, without phase delay, heat pulses which propagate outwards. At $R \approx 3.2$m, $P_{e,coll}$ induces a second T_e modulation with the significant phase delay indicated above. A third contribution to the T_e modulation is caused by the ion modulation through $\chi_{e-i,s}$, inducing a

modulation of T_e related to that of R/L_{Ti}. The modulation amplitude of R/L_{Ti} is zero in the plasma center, exhibits a maximum just outside of the maximum of $P_{i,coll}$ ($R \approx 3.3$ m) and decreases towards the edge. The amplitude profile of the T_e modulation induced by $\chi_{e-i,s}$ has a similar shape but it is, per nature, out of phase with respect to that of R/L_{Ti}. Therefore, it is roughly out of phase with that of the T_e modulation excited by the two electron heat sources and can efficiently reduce the phase delay in the off-axis region. These three components contribute to the measured T_e modulation and can explain the shape of the phase at 8Hz. We now turn to the 20Hz case. The T_e profile is well also reproduced. The experimental amplitude and phase profiles exhibit a usual shape. The absence of the non-monotonic behaviour in the phase is attributed to the fact that the contribution of $P_{e,coll}$ strongly decreases at higher frequency, as well as the effect of $\chi_{e-i,s}$ on the modulation. However, the simulations do not reproduce the modulation data correctly. Whereas, as suggested by case c, the amplitude could be better reproduced by further increasing $P_{e,direct}$, the slope of the phase is not matched at all. A better match would require higher transport leading to a strong mismatch of the *Te* profile and this discrepancy is still under investigation.

Alternatively to the existence of the off-diagonal term $\chi_{e-i,s}$, the non-monotonic phase profile at 8Hz and the flat one at 20Hz could be caused by power deposited off-axis with a small phase delay, therefore not induced by fast ions. Indeed, it is possible to simulate the phase correctly adding an arbitrary electron heating profile with zero phase delay, of different magnitude at 8 and 20Hz though. In fact, off-axis electron heating due to mode conversion cannot be excluded, [27]. However, the TORIC code, [28], indicates that its radial position is not enough off-axis and its deposition width too narrow, to reproduce the data correctly.

CONCLUSION

The main goal of the experiment which consisted in investigating ion heat trasnport with power modulation, has been achieved. The validity of the T_i modulation for transport studies has been demonstrated, yielding for the first time a direct experimental measurement of the ion stiffness. The value found in the present work is moderate which is attributed to the presence of ^{3}He and to the situation $R/L_{Te} > R/L_{Ti}$, as indicated by the non-linear gyrokinetic results, which agree well with the experiment. The ^{3}He ICRH scheme in deuterium works well for ion modulation and is, to our knowledge, the best possibility for such experiments, despite the accompanying electron heating. The situation in the electron channel is complex because it involves two heating sources with different time scales and a significant contribution from the off-diagonal term driven by R/L_{Ti}. Our study indicates that the electron stiffness, $\chi_{e-i,s} \approx 0.15$, is weak and that the cross term $\chi_{e-i,s} \approx 0.25$ is important. This is due to the ITG-dominated regime. The comparison of the ICRF deposition calculated by PION and SELFO for the scheme used here suggests that the fraction of direct electron heating yielded by SELFO might be too low whereas the collisional electron heating from PION is too low. An additional off-axis component to electron heating cannot be excluded but it is not identified yet.

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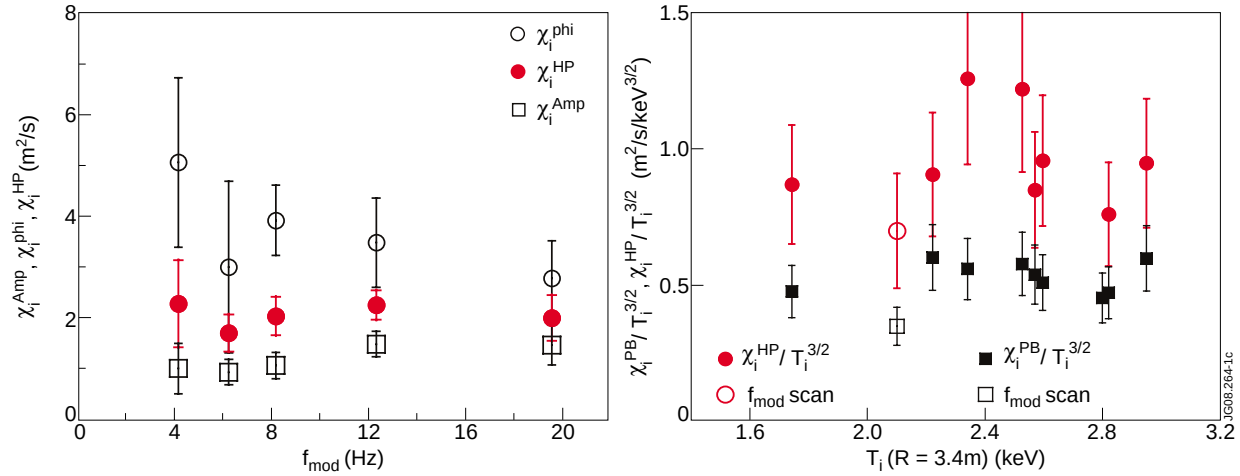

Figure 1: Experimental results from perturbative transport analyzed at R = 3.4m. Left plot: Frequency dependence of χ_i^{phi} , χ_i^{Amp} and χ_i^{HP} versus fmod. Right plot: normalized values of χ_i^{HP} and χ_i^{PB} versus ion temperature from the NBI power scan, the open symbols are representative of the fmod scan results.

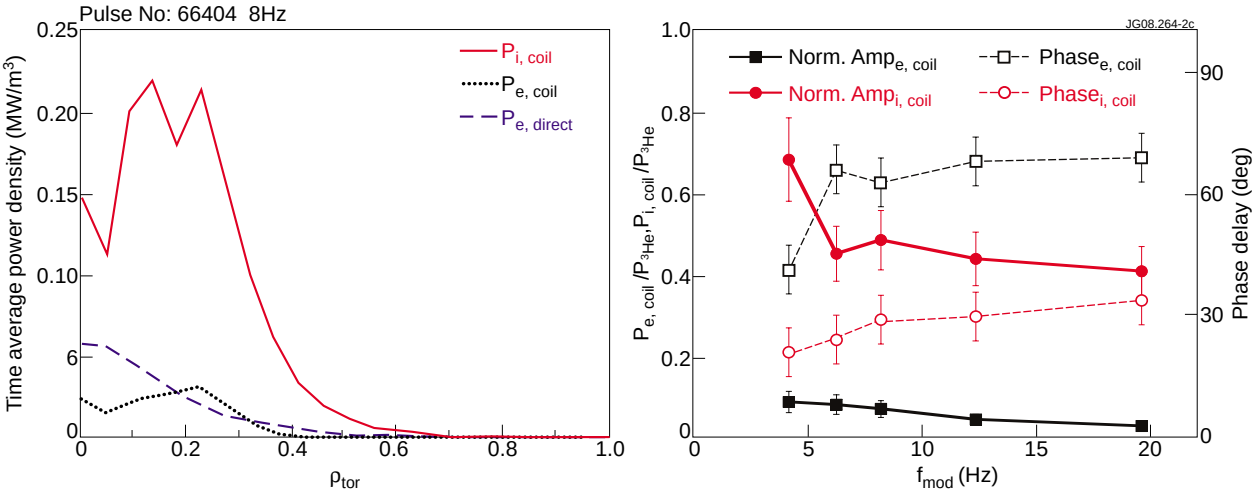

Figure 2: Results from PION for modulated ICRF. Left plot: profiles of deposited time-averaged power densities. Right plot: Modulation amplitude, normalized to the power absorbed by the minority, and phase delay of the volume integrated of $P_{i,coll}$ and $P_{e,coll}$ versus f_{mod}.

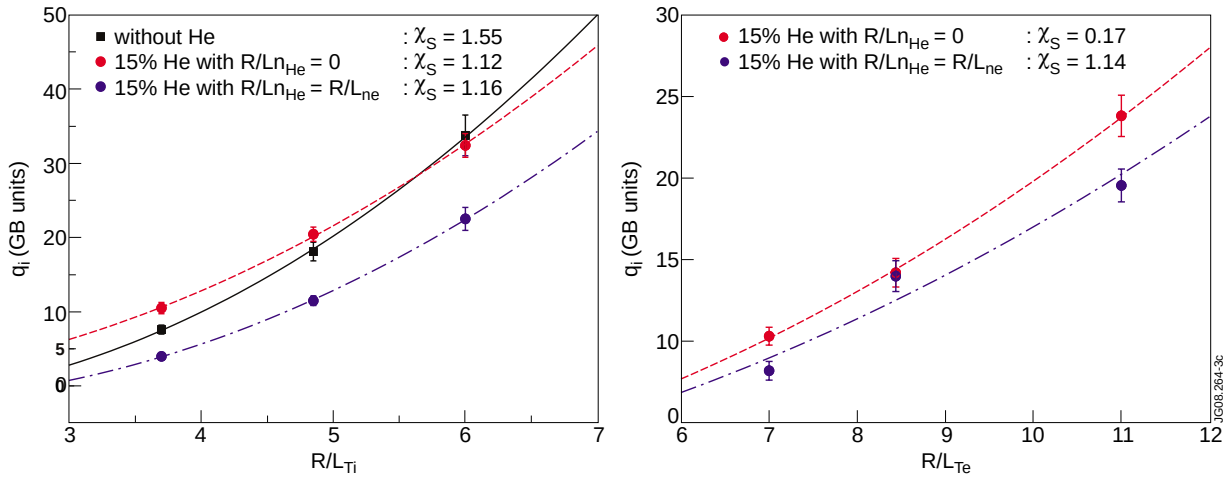

Figure 3: Diagonal heat transport: Ion and electron heat fluxes, normalized by the gyro-Bohm factor, versus respective normalized gradients. The symbols and colors correspond to different assumptions for the profile of [^{3}He], as indicated in legend and text.

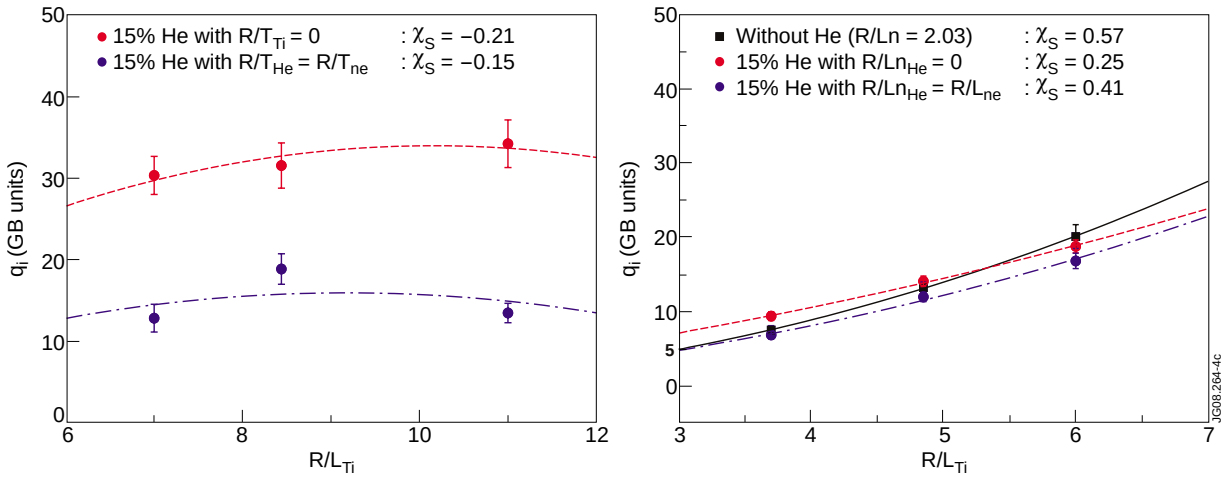

Figure 4: Off-diagonal transport: normalized q_i and q_e crossed normalized gradients.

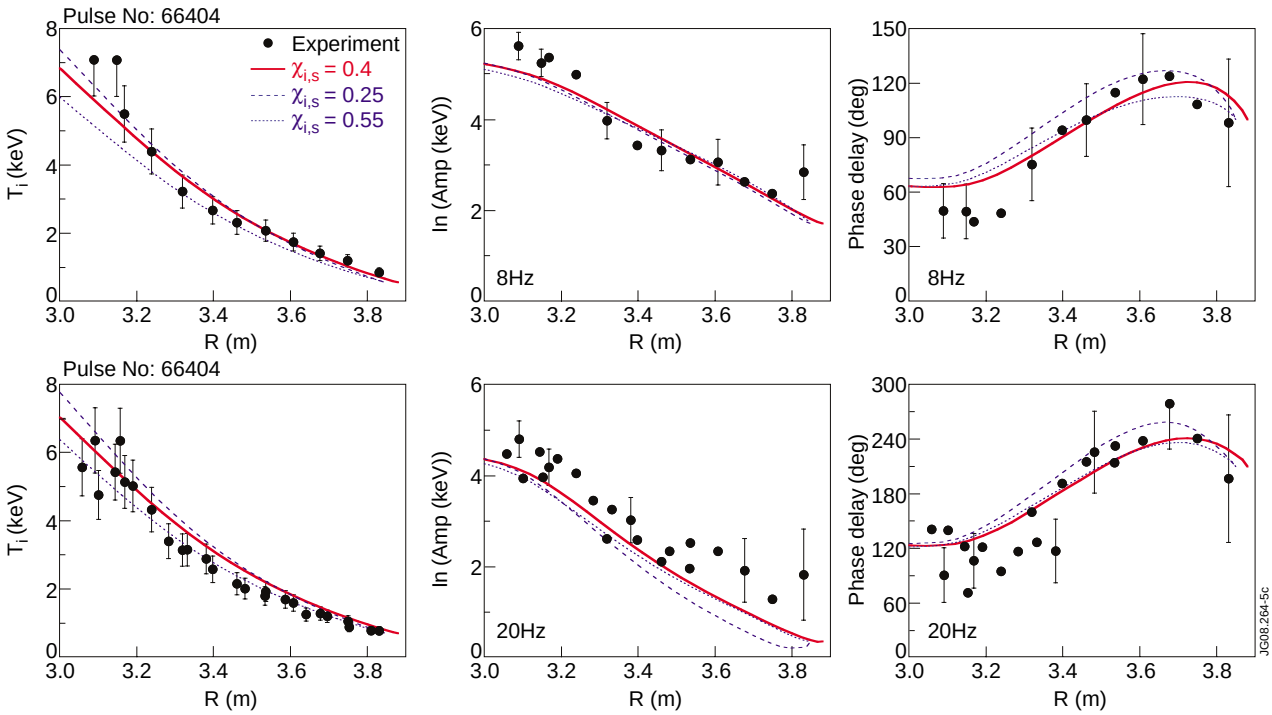

Figure 5: Time-averaged T_i, amplitude and phase of T_i modulation at 8 (top) and 20Hz (bottom). Note the different Y-scales of the phase in agreement with the steeper slope at 20Hz.

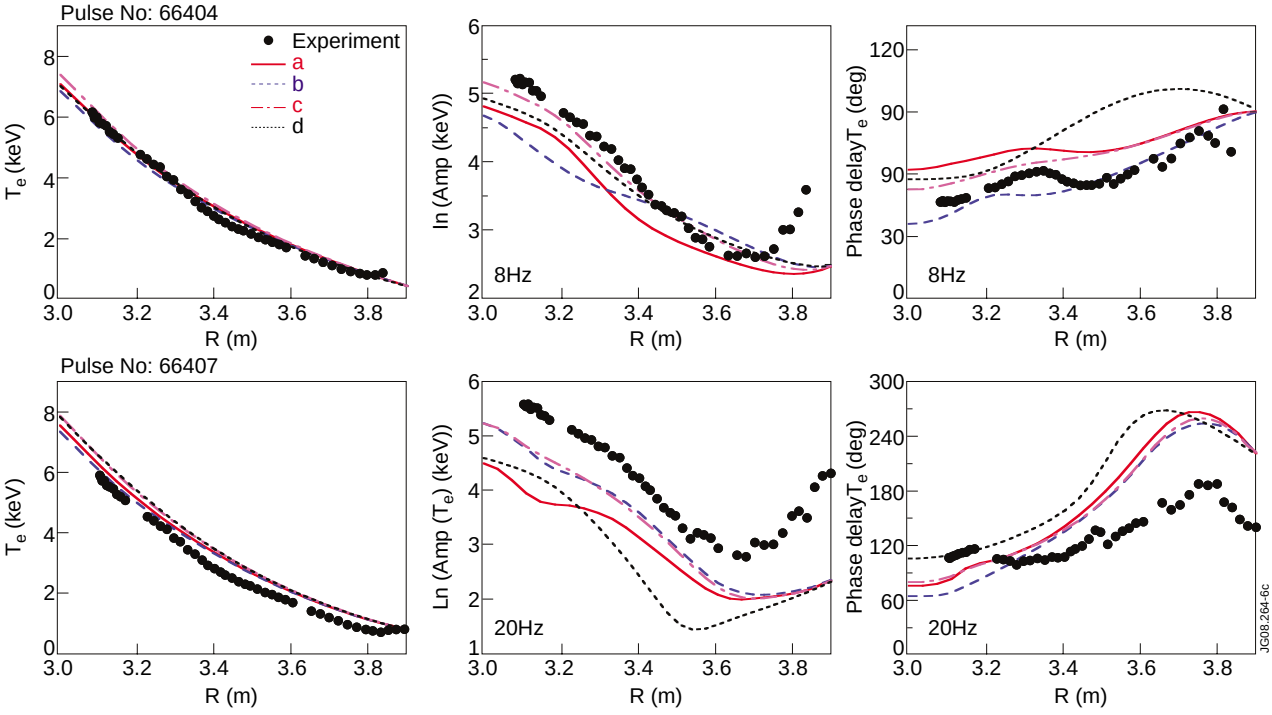

Figure 6: Time-averaged T_e, amplitude and phase of the T_e modulation at 8 and 20Hz.