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HEAT TRANSPORT IN PBX-M HIGH β_p PLASMAS

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Heat Transport in PBX-M High β_p Plasmas

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Abstract

PBX-M high beta poloidal discharges routinely transition into the H-mode regime: typically, a quiescent phase followed by an MHD active phase characterize the H-mode period. An analysis of the energy transport during these phases is conducted using the experimental data and the TRANSP code; effective diffusivities are computed to quantify the energy transport of the thermal component of the plasma. Compared to the L-mode, the quiescent H-phase is characterized by a decrease of the thermal ion energy transport and a flattening of the associated effective diffusivity profile. An error analysis is presented. Enhanced fast-ion losses are observed during the MHD active phase: particles in the lower end of the fast-ion energy spectrum with large perpendicular velocity component are predominantly affected. These losses must be taken into account in the analysis in order to reproduce the measured stored energy and time evolution of the neutron production rate during the MHD active phase. Conclusions of this analysis are: (i) during the MHD active phase, the thermal ion diffusivity remains close to its value and profile shape obtained at the end of the quiescent H-phase, suggesting within the uncertainty of this analysis that the MHD activity does not affect the thermal plasma energy transport; and (ii) the observed beta saturation results from the enhanced losses in the fast-ion population. An analysis without inclusion of enhanced fast-ion losses would lead to different conclusions, but would fail to reproduce experimental measurements. Throughout the H-mode

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period, the electron effective diffusivity remains lower than the ion effective diffusivity.

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I. INTRODUCTION

One important result from the experimental research on tokamaks is the H-mode regime in which the energy confinement time can be a factor of two greater than in the L-mode.¹ The H-mode, first reported by the ASDEX team,² has been observed in many tokamaks. Because this confinement regime could be important in the design of fusion reactors, it has been the subject of different studies. In ASDEX, the better confinement of the H-mode regime has been linked to a reduction of the electron thermal transport.³ In JET, a reduction of the ion thermal transport is observed during the H-mode phase.⁴

High beta poloidal discharges in PBX-M typically enter the H-mode regime. Making use PBX-M full array of diagnostics and of the TRANSP^{5,6,7} code, we will discuss the thermal transport during different stages of the discharge. In particular we will "walk through" the transition and observe that it marks the onset of a decrease of the effective ion diffusivity, which is more pronounced in the plasma outer region. This process, which occurs during the early times of the quiescent H-phase, flattens the ion diffusivity profile. The quiescent phase is followed by an MHD active phase, during which a soft rollover of the stored energy and neutron production rate occur, although the discharge remains in the H-mode. During that time, enhanced fast ion losses are observed which are associated with MHD activity. The energy and momentum distribution of the lost ions were quantified by a multi-sightline charge exchange neutral analyzer. The inclusion of these losses in the transport analysis indicates that, while part of the fast-ion stored energy is lost, the confinement properties of the thermal component of the plasma remain nearly unaffected during this later stage.

In Section II, we review briefly the key features of the PBX-M tokamak. Section III elaborates on high β_p plasmas. Section IV surveys the experimental documentation of these plasmas. In Section V, we present and discuss results of transport analyses over a time interval including the end of the L-mode, the quiescent H-mode, and the MHD active H-phase.

II. THE PBX-M TOKAMAK

The objective of the PBX-M project is to understand and improve tokamak plasma stability and confinement with an aim towards demonstrating access to the regime of second stability to high- n ideal ballooning modes.⁸ To achieve these goals, the PBX-M program includes extensive plasma shaping capability (inboard indented cross-section), active profile control (current and pressure), and passive stabilization of low- n surface MHD modes by a close-fitting conducting shell.

Inboard indentation shaping improves the "tokamak" magnetic well by enhancing the inside good curvature region. This shaping has inherent stabilizing properties against ideal MHD ballooning⁹ and localized interchange modes.¹⁰ Specifically, calculations have demonstrated that the second stability regime can be made accessible with naturally occurring values of the central current density, $q_0 \approx 1$. This is primarily due to the fact that such configurations can produce, in the region of bad curvature, strong local magnetic shear along with a short connection length.^{11,12} Another favorable consequence of the indented shape is that the resultant high triangularity in the core region of the plasma can improve Mercier¹³ stability. Triangularity also has a beneficial effect

on the beta limit of peaked pressure profiles¹⁴. Finally, with respect to confinement enhancement, the inboard indentation shaping can improve the trapped-particle drift properties. This is beneficial in that unfavorable precession drift resonances are known to drive not only electrostatic microinstabilities,¹⁵ but can also cause fast ion losses near the injection energy in neutral-beam heated tokamaks.

Different techniques can implement active profile control on PBX-M. Neutral beam heating, pellet injection, and IBW heating have been used to modify the pressure profile. Alteration of the current profile was achieved by neutral beam counter-injection and also by fast plasma current ramping. An LHCD system is presently being installed which will drive current in the outer region of the plasma. Profile diagnostics are used to ascertain the effects of these techniques, including a motional Stark effect (MSE) measurement of the local magnetic shear (through a determination of the local field pitch).¹⁶

The design of the PBX-M tokamak introduced a close-fitting passive shell for the stabilization of the $n=1,2$ external kink modes and the $n=0$ axisymmetric modes. (The external kink mode was found to be a β -limiting factor in the operation of the PBX device.) A more comprehensive overview of the device, performance, and regimes can be found elsewhere.¹⁷

III. PBX-M HIGH BETA POLOIDAL PLASMAS

High beta poloidal, β_p , discharges were produced at a nominal constant plasma current, I_p , of 340 kA and toroidal field, B_t , of 1.35 T with D^0 neutral beam injection power of 5.5 MW into D^+

plasmas. (See Table I for definition of β_p .) Table I lists some parameters of these plasmas at the end of the quiescent H-phase. The minor radius, a , was nominally 0.28 m. Note that in the following, "minor radius" will refer to the midplane halfwidth. The major radius of the geometric center, R_0 , was 1.65 m. From 0.4 s to 0.49 s, the plasma shape parameters indentation, ι , elongation, κ , and triangularity, δ , range 0.14-0.20, 1.70-1.85, and 0.31-0.49 respectively. See Fig. 1 for the definition of these parameters. The Troyon parameter¹⁸ I_p/aB_t was 0.9 and $\beta_t/(I_p/aB_t)$ reached 4.5, where β_t is the volume averaged toroidal beta. The PBX-M neutral beam injection system includes four beam injectors: two at near normal incidence and two with a finite tangential component (see Table I).

Fig. 2 shows the time evolution of selected parameters for one high β_p discharge. The plasma current (top panel) was kept constant from 0.3 s on; β_p exceeded 2.0 for times between 0.45 and 0.55 s. The neutral beam injections were staggered sequentially; the four "on" times were set at intervals of 0.05 s from 0.25 s to 0.4 s (second panel). Auxiliary heating began with the two "tangential" beams, then continued with perpendicular injection. Full beam power was maintained from 0.4 s to 0.55 s. These discharges typically exhibited an H-mode transition: a drop in the D_α signal followed by an increase in the rate of rise of the density and stored energy. The transition occurred at about 0.375 s as can be seen in the third panel of Fig. 2. From the beginning of the neutral beam injection up to 0.44 s, the stored energy increased almost linearly with absorbed power (fourth panel). This behavior resulted from the time staggering of the neutral beam sources and the occurrence of the H-mode. Later on the

stored energy saturated and began a rollover. The beta saturation (0.46 s - 0.50 s) coincided with the onset of MHD activity in the form of low-n global modes (observed over the whole plasma column), isolated ELM activity, and enhanced fast-ion losses (see below). At 0.5 s, a giant ELM appeared followed by a strong $n=1$ mode. The stored energy rollover slowed down and for some time the plasma energy content increased before a final descent beginning at 0.54 s. In the fifth panel, one can see a blow up of the Mirnov coil trace associated with the "continuous" MHD mode. In the following, we will concentrate on the time interval 0.36 s to 0.5 s. Another paper in preparation will discuss the details of the MHD activity.

IV. EXPERIMENTAL DOCUMENTATION OF HIGH β_p PLASMAS

A documentation of these discharges was made with the complete array of PBX-M diagnostics. These included a full profile (55 spatial points) of the horizontal midplane electron temperature, $T_e(R)$, and density, $n_e(R)$, measured by Thomson scattering, nine-channel ion temperature $T_i(R)$ and toroidal velocity $v_\phi(R)$ profiles by charge exchange recombination spectroscopy (CXRS) covering the outer half the plasma, Z_{eff} profiles computed from the visible continuum and Thomson scattering data, and radiated power profiles obtained from an array of 15 tangentially viewing bolometers located at the midplane. Single time point Thomson scattering measurements from similar discharges were concatenated to produce a time evolution of $T_e(R)$ and $n_e(R)$. This procedure took into account the actual shot to shot time jitter of the H-mode transition by renormalizing the times of the measured profiles with respect to the H-transition and onset of MHD activity. The concatenation attempted to reproduce a (typical) discharge with a transition in the vicinity of 0.375 s, an MHD free

H-mode phase ending at ≈ 0.46 s, and an MHD active phase lasting until 0.5 s. The Thomson scattering time slices are at 0.24, 0.27, 0.30, 0.33, 0.395, 0.46, and 0.49 s. Plots of the Thomson scattering data concatenation can be seen in Fig. 3; solid-line profiles (against major radius) indicate concatenated data. Z_{eff} profiles were concatenated similarly. The $T_i(R)$, $v_\phi(R)$, and bolometer data are taken from representative shots. The T_i profile time points are at every 0.02 s from 0.36 s to 0.46 s, plus one at 0.49 s. For times prior to 0.36 s, T_i was assumed to increase linearly with time from $0.7 \times T_e$ at the end of the ohmic phase to the value measured at 0.36 s.

The plasma outer boundary and shape were computed by matching measured flux differences with the FQ equilibrium code¹⁹ at each Thomson scattering time point. This information is input into TRANSP, and the internal equilibrium is calculated by solving the Grad-Shafranov equation using the TRANSP current and pressure profiles. We can see in Fig. 4 a plot of such an equilibrium at 0.49 s. Also shown are the actual locations of the passive plates and their representations used for the TRANSP analysis, to be discussed later on.

Coincident with the onset of the MHD activity, enhanced fast-ion losses were observed with a multi-sightline charge exchange neutral analyzer viewing the horizontal midplane of PBX-M. The losses were most conspicuous along the most perpendicular sightlines of the analyzer, and they appeared in the presence of weakly turbulent MHD activity (mentioned above) as the beta parameter saturates. Unlike the fishbone case,²⁰ where the effect was clearest near the injection energy (E_{inj}), ions below $E_{\text{inj}}/2$ were predominantly affected during this phase. We can see in Fig. 5 a comparison of the energy spectrum of the fast ions before and

after beta saturation. Because the charge-exchange signal is a line-integrated quantity, it reflects a combination of fast ions expelled to the plasma edge during MHD activity, and the depleted ion distribution remaining in plasma center. Although the detected flux is not a direct measure of the magnitude of the fast-ion losses, it can still be used to parametrize the energy and momentum of the escaping fast neutrals. The enhanced losses, during beta saturation, can be seen for energies lower than 15 keV. The measurements are consistent with a loss cone defined by $v_{fast}^{II}/v_{fast} \leq 0.25$ and $E_{fast} \leq 15$ keV. We will refer to these Enhanced Fast-Ion Losses as "EFIL." It is of interest to note that during the MHD active phase, the ion temperature fell by more than 20% while the electron temperature remained unaffected (see Fig. 8). We will elaborate on this point later.

V. THERMAL TRANSPORT ANALYSIS

A TRANSP analysis is a valuable tool for integrating the experimental data and determining the power balance of each species. The portion of the power loss which is not accounted for, in the thermal plasma, is phenomenologically assumed to be diffusive, and effective thermal diffusivities are computed. We will simply refer to these thermal transport coefficients as the ion and electron diffusivities: χ_i and χ_e . A label will be attached to the diffusivity (i.e., χ_i^{LABEL}), when different computations need to be identified. These coefficients provide a way to quantify the transport. The ion and electron convection terms were set to $\frac{3}{2} T_i \Gamma_i$ and $\frac{3}{2} T_e \Gamma_e$ respectively, where Γ_i and Γ_e are the respective particle fluxes. As we have seen above, we have good profile documentation of the thermal plasma,

but there is no direct measurement of the heating beam deposition profile. This information is nevertheless critical, since most of the input power is provided by these fast particles. The ionization of the fast neutrals, as well as the capture and slowing down of the resulting fast ions, involve classical processes which are well understood.²¹ The TRANSP code has a sophisticated means (using a Monte Carlo beam deposition calculation) of modelling these processes and computing the distribution function of the fast particles. The calculations rely on the tokamak and the injector parameters as well as the measured thermal plasma profiles. Finally, TRANSP can also compute measurable parameters, such as stored energy and neutron production rate, which are not part of the input data. One can then compare these "simulated diagnostics" to actual measurements in order to ascertain the validity of a particular transport analysis.

For the purpose of our discussion, we can consider the plasma as consisting of three components: the fast ions, the thermal ions, and the thermal electrons. When referring to the fast ions, we will always use the qualifier "fast." We use the notation $P_{\text{sink}}^{\text{source}}$ for some of the power fluxes and $W_{\text{specie}}^{\text{component}}$ for stored energies, the "component" label is used for the fast ions. The sub- and super-script "fast" refers to the fast-ion population. Some established notations like P_{rad} for the radiation loss and Q_{ie} for the ion-electron exchange term have been kept.

The transport analyses presented here span the time interval 0.35 s to 0.5 s. This interval includes the end of the L-mode phase, the H-mode transition, the quiescent H-phase, and the period where non-classical fast-ion losses (EFIL) are observed coincident with continuous MHD activity and

ELMs. During this whole time interval, conduction is the dominant loss mechanism for the ions. We can see in the top portion of Fig. 6, a time history of the relevant terms of the ion power balance at $r/a=0.5$. The conduction term $P_{\text{cond}}^{\text{ion}}$ balances more or less the heating term $P_{\text{ion}}^{\text{fast}}$. The time derivative of the ion stored energy $\dot{W}_{\text{ion}}$ appears as a virtual loss term indicated by a dotted line. The ion-electron exchange term Q_{ie} , ion-convection loss $P_{\text{conv}}^{\text{ion}}$, and time derivative $\dot{W}_{\text{ion}}$ remain small compared to the ion-conduction term. Hence the effective diffusivity χ_i is fairly insensitive to the details of Q_{ie} , $P_{\text{conv}}^{\text{ion}}$, and $\dot{W}_{\text{ion}}$. A similar plot for the electron power balance is shown at the bottom for Fig. 6; the conduction loss $P_{\text{cond}}^{\text{elec}}$ is the most important term but others like P_{rad} and Q_{ie} are also significant.

A. H-mode transition and quiescent phase (0.35 to 0.46 s)

In Fig. 7, we see a plot of the time evolution of the ion diffusivity and the electron diffusivity for three values of the minor radius: $a/3$, $a/2$ and $2a/3$. This analysis assumes the fast ions to behave classically. We will first concentrate on times earlier than 0.46 s. A stair-step trace indicates the "on" times of the two last neutral beam injectors. One sees that χ_i varies substantially during the course of its time evolution, but stays higher than χ_e , which remains unchanged within the precision of the range bars. A discussion of these bars is given below. The ion diffusivity falls by a factor of ≈ 3 at $r = a/2$ going from the L-phase to the end of the MHD free H-phase. The ion diffusivity remains the same or continues to decrease even when the last neutral beam injector (≈ 1.2 MW) is turned on at 0.4 s. At

the end of the quiescent H-phase, χ_i and χ_e are comparable as was also observed in DIII-D.²²

The temporal resolution of the analysis depends on the number of experimental profile time points. For the time interval mentioned above, the ion diffusivity is chiefly determined by the ion temperature, which was measured every 0.02 s. By inspecting trace "a/2," one can extract an "analyzed" transition time — a knee in the χ_i trace — of 0.36 s, which is a little off of the targeted 0.375 s, but is acceptable in view of the analysis time resolution. The fact that for $r=2a/3$, the transition appears to occur earlier could be related to the T_i data treatment (see below). The reduction of χ_i occurs later for $r=a/3$. The χ_i profile is radially hollow (larger value on the outside) during the L-mode, but becomes nearly flat during the quiescent H-phase.

In addressing the effects of experimental uncertainties on the transport analysis, a complete and systematic analysis of all the effects of all the possible experimental errors would be a formidable task that is not considered here. Instead, we will concentrate on the most likely instrumental causes of error. As mentioned earlier, the bolometer array is viewing tangentially in the machine midplane, where most of the plasma interaction with the first wall (indentation coil armor plate, outer limiter and conducting shell) occurs. This radiation, which occurs outside the plasma, effectively causes an overestimate of the radiation loss, P_{rad} , inside the plasma. Another difficulty in determining the diffusivities may arise from the fact that at some time points, $T_i \approx T_e$ over a substantial portion of the minor radius as can be seen on Fig. 8. This situation can lead to uncertainties in the separation between the electron and ion channels. The two effects just mentioned are believed to be the primary cause of

uncertainty in the computation of the heat diffusivities. For this reason, we conducted a study of the uncertainty on the diffusivity values by running analyses (with TRANSP) using different assumptions and comparing the diffusivities obtained. In order to ascertain the effects of the similarity of the T_i and T_e profiles, we ran analyses with the temperatures changed to values representative of the experimental error bars. In order to compute an upper limit to the uncertainty caused by the potential overestimation of the radiation losses, analyses were run with P_{rad} reduced by a factor of 100. We can see, in Table II, a list of the assumptions made for the uncertainty analysis. The heat diffusivities shown in Fig. 7 correspond to the "0" analysis (no assumptions). The "range bars" shown in this figure represent the limit of the respective diffusivities according to analyses 1 through 5, and in that sense are not "true" error bars, although they are suitable to ascertain the uncertainty of the evaluation of the diffusivities. The electron diffusivity trace sits nears the bottom of its range because of the sensitivity of the χ_e computation to P_{rad} .

Another possible cause of error could come from the assumption made about the ion temperature; we mentioned earlier that for times earlier than 0.36 s, T_i was assumed to increase linearly with time from $0.7 \times T_e$ at the end of the ohmic phase up to the first value measured at 0.36 s. This hypothesis might be underestimating the ion temperature since the density is lower during the early phase of NBI heating. In order to determine the effects of an ion temperature underestimation at early times, an (extreme-case) analysis was made where for times earlier than 0.36 s, T_i was set to the value measured at 0.36 s. The result of this analysis is indicated by the dotted trace in Fig. 7. Only at $r = 2a/3$ does χ_i differ from the previous result, and this only for times earlier than 0.36 s.

The onset of the χ_i (at $r = 2a/3$) decrease occurs at the same time as that for $r = a/2$. The time evolution of χ_i at $a/3$ and $a/2$ are not affected. The electron diffusivity is also not affected.

The source of error considerations just described do not change our conclusion that a decrease of the ion diffusivity is the earmark of the quiescent H-mode in PBX-M high β_p discharges. The reason why the temperature experimental-error-range analyses do not change the result is that the ion-electron exchange Q_{ie} is not large compared to the other terms of the power balance of the thermal species. The time evolution of the χ_i is not affected, for times greater than 0.36 s, by the assumption made about early values of T_i . The limited time resolution makes it difficult to characterize further the fine details of the profile evolution of the ion diffusivity.

B. Enhanced fast-ion loss phase ($0.46 \text{ s} < t < 0.5 \text{ s}$).

Two approaches are used regarding the computation of the fast ion population during the MHD active phase. In one case, TRANSP is run with its usual fast-ion package where these particles interact classically with the target plasma and also each other; the results discussed in the previous section and shown in Fig. 7 correspond to these calculations. In the second approach, the loss cone based on the charge exchange neutral analyzer data is introduced in the computation of the fast-ion population. During the Monte Carlo computation, fast ions found in the loss cone ($v_{fast}^{\parallel}/v_{fast} \leq 0.25$ and $E_{fast} \leq 15 \text{ keV}$) are assumed lost, resulting in the additional loss term P_{EFIL}^{fast} . This loss channel is opened for times larger than 0.46 s with an average loss time, τ_{EFIL} . We will compare the results of the EFIL analysis

with those obtained with a classical fast-ion-loss analysis, referring to the latter treatment as CFIL (Classical Fast-Ion Losses).

We can see in Fig. 8 the predicted time evolution of the the stored energy from the CFIL and EFIL analyses. The stored energy obtained from the equilibrium code FQ (accuracy of ± 3 kJ) at 0.49 s can be considered as an experimental checkpoint. It can be seen that the CFIL projection overestimates the stored energy. On the other hand, by using the loss cone mentioned above and setting τ_{EFIL} to 10^{-4} s, the EFIL prediction comes into better agreement with FQ.

As a further means of establishing a choice between the CFIL or EFIL models, we show in Fig. 10 a plot of the time evolution of the neutron rates predicted by CFIL and the EFIL analyses. Because the neutron rate is mainly due to the beam-target (78%) and beam-beam (17%) interactions, its computation is sensitive to the noise in the Monte Carlo calculations. This noise can be estimated from the relative differences between the outputs of analyses with identical inputs; this estimation can be made for times smaller than 0.46 s where many such analyses were done. The trace shown in Fig. 10, for times smaller than 0.46 s, is the average of five identical analyses and the error bars shown are the calculated variances. One can see that the Monte Carlo noise is on the order of 1×10^{13} n/s. Such error bars have been transposed to the TRANSP neutron rate prediction at 0.49 s. Also shown in Fig. 10 is a trace ("EXP") obtained from a neutron detector: the available data are from 0.46 s to 0.54 s. The detector was not absolutely calibrated and the data is normalized to the TRANSP prediction at 0.46 s. The interest of this plot stems from the comparison of the time evolution of the anticipated neutron rate and the experimental data. On can see that the CFIL prediction quickly arrives at an over-forecast of the

neutron rate. On the other hand, the EFIL prevision shows an excellent match to the time variation of the experimental trace. This prediction is extracted from the exactly same TRANSP analysis (same loss cone and τ_{EFIL}) used earlier in the stored energy comparison.

The $P_{\text{EFIL}}^{\text{fast}}$ loss term incurs a reduction in the fast-ion power transferable to the thermal species, and, to a lesser extent, a diminution of classical fast ion losses due to charge exchange and bad orbits. In order to achieve an accurate calculation of the bad orbit losses, care was taken to prepare the analyses with a first wall representation, shown in Fig. 4, consistent with the PBX-M passive shell and material limiter. Table III lists some of the relevant parameters for times close to 0.49 s. The subscript: CX and BO correspond respectively to the charge exchange and bad orbit fast-ion losses.

From the numbers of Table III, we can see that the principal result associated with the inclusion of EFIL effects into the TRANSP calculation is to drive the $P_{\text{EFIL}}^{\text{fast}}$ loss to 1.25 MW. Because the lower end of the fast-ion energy spectrum is depleted, the heat transfer to the thermal ions is primarily reduced, while the electron auxiliary heating is less affected.^{2,3} The heat transfer to the thermal ions suffers a 43% drop when $P_{\text{ion}}^{\text{fast}}$ is reduced from 2.34 to 1.33 MW; the electrons suffer a 13% loss when $P_{\text{elec}}^{\text{fast}}$ falls from 0.76 to 0.66 MW. This higher drop of heating power to the ions compared to the electrons is consistent with the observed behavior of the temperatures, where T_i falls during the MHD active phase while T_e remains unaffected. The larger part of the fast-ion stored energy loss is from the perpendicular component. The small increase in the ion thermal stored energy, W_{ion} , and rotation energy, stems from a larger thermal ion population necessary for a charge balance consistent with the measured

Z_{eff} profiles. The total stored energy falls by 3% to 159 kJ, which is consistent with experimental observations. This fall is due to the fast-ion loss of stored energy.

The decrease of the ion heating associated with the inclusion of EFIL effects incurs a reduction of the conduction loss (in the ion power balance) compared to CFIL calculations. Nevertheless, conduction remains the principal ion loss mechanism. The changes to the electron power balance occasioned by EFIL effects are small. One can see in Fig. 11 the time evolution of the χ_i^{EFIL} and χ_e^{EFIL} extracted from the EFIL transport analysis mentioned above. The ion energy balance is modified by the reduction of P_{ion}^{fast} with the effect that the computed transport loss is lowered, resulting in $\chi_i^{EFIL} \leq \chi_i^{CFIL}$. During the MHD active phase, χ_i^{EFIL} maintains a profile close to the one it had at the end of the quiescent H-mode. This differs from the classical analysis, shown in Fig. 7, where the χ_i^{CFIL} profile resumes the inverted feature observed during the L-mode.

VI. CONCLUSION

We have studied the heat transfer during the H-mode stages of PBX-M high β_p discharges. Making use of the time dependent code TRANSP, we have quantified the thermal heat losses through the effective diffusivity coefficients χ_i and χ_e . The improvement of the energy confinement observed during the quiescent H-phase occurs through the ion channel; the transport analysis indicates a progressive reduction of χ_i and flattening of its profile. Within the error analysis performed, χ_e remains constant, has a flat profile, and is lower than χ_i . A straightforward (classical) transport analysis of the MHD active phase would reveal a behavior where χ_i increases and resumes an L-type inverted profile. The MHD activity could

then be thought responsible for the worsening of the (thermal plasma) energy confinement, but such an interpretation fails to reproduce the stored energy and neutron rate time evolution. Secondly, the experimental evidence indicates that the plasma — with its small ELM activity — is still operating in the H-mode, and it would be difficult to surmise a L-type χ_i profile in this situation. An analysis including the measured enhanced fast-ion losses (EFIL) in the Monte Carlo calculation of the fast-particle population, however, produces a good match to the stored energy and the neutron rate time evolution. Because the EFIL appear at the lower end of the fast-ion energy spectrum, the auxiliary heating of the (thermal) ions is principally affected — a reduction of the order of 40%. This change in the ion power balance modifies the computation of the effective ion diffusivity; instead of resuming an L-type profile, χ_i and its profile, throughout the MHD active phase, remain close to what they were at the end of the quiescent phase. Therefore, we conclude that, within the uncertainty of this analysis, the energy transport of the thermal plasma is unaffected by this global MHD activity.

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Table I. Typical high β_p plasma parameters at end of quiescent H-phase, and neutral beam injection parameters.

B_T	1.35 T
I_p	340 kA
R_0	1.65 m
l	0.18
κ	1.74
δ	0.40
a	0.27 m
$\beta_p = \frac{8}{3} W_{\text{total}} / (\mu_0 R_0 I_p^2)$	2.0 (≤ 2.2)
$I_p / (a B_T)$	0.9
$\beta_t / (a B_T)$	4.5
$T_i(0)$	≤ 4.5 keV
$\overline{n_e}$	$4.3 \times 10^{19} \text{ m}^{-3}$
$n_c(0)$	$5.6 \times 10^{19} \text{ m}^{-3}$
$T_e(0)$	2.1 keV
# of beam @ tangency radius	2@1.30 m, 2@0.35 m
Beam angle of incidence @ R_0	52° , 12°
Beam energy	37-42 keV
P_{heat} (beam + ohmic)	(4.3 MW + 0.05 MW)
$q(0)$ (measured: MSE)	0.7
q_{edge}	4.7
W_{tot}	160 kJ
τ_E	$0.034 \text{ sec} = 2.4 \times \tau_E^{\text{ITER89-P}}$
$n_c(0) \tau_E T_i(0)$	$7 \times 10^{18} \text{ m}^{-3} \text{ s keV}$

Table II. Diffusivity uncertainty analysis. List of the different analyses and their assumptions used in the uncertainty analysis.

Analysis #	T_i assumption	T_e assumption	P_{rad} assumption
0 (original)	T_i	T_e	P_{rad}
1	T_i	T_e	$P_{rad}/100$
2	$1.1 \times T_i$	$0.9 \times T_e$	P_{rad}
3	$1.1 \times T_i$	$0.9 \times T_e$	$P_{rad}/100$
4	$0.9 \times T_i$	$1.10 \times T_e$	P_{rad}
5	$0.9 \times T_i$	$1.10 \times T_e$	$P_{rad}/100$

TABLE III: Comparison of plasma parameters for CFIL and EFIL analyses at end of MHD active phase. Quantities in single walled boxes are related to fast ions. Quantities in double walled boxes to be compared with experimental data. Note that for the neutron rate (R_n), we are interested in the time evolution. (See text.)

FIL		CFIL	EFIL
P_{ion}^{fast}	MW	2.34	1.33
P_{elec}^{fast}	MW	0.76	0.66
P_{CX}^{fast}	MW	0.33	0.30
P_{BO}^{fast}	MW	0.69	0.60
P_{EFIL}^{fast}	MW	—	1.25
$P_{CX+BO+EFIL}^{fast}$	MW	1.02	2.15

R_n	n/s	1.1×10^{14}	1.0×10^{14}
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FIL		CFIL	EFIL
$W_{fast}^{\perp}$	kJ	26.4	21.1
$W_{fast}^{\parallel}$	kJ	15.5	14.2
W_{fast}^{tot}	kJ	41.9	35.3
W_{ion}	kJ	46.6	48.4
W_{elec}	kJ	69.1	69.1
W_{rot}	kJ	5.8	6.0
W_{thrm}	kJ	121.5	123.5
W_{tot}	kJ	163.3	158.8

FIGURE CAPTIONS

Fig. 1. Plasma boundary and shape parameters: (K) elongation, (l) indentation, and (δ) triangularity.

Fig. 2. Time evolution of plasma parameters of high β_p discharge. Solid-line profiles against major radius indicate concatenated data.

Fig. 3. Thomson scattering data concatenation. Electron temperature and density plotted against major radius and time.

Fig. 4. Plasma equilibrium during MHD active phase and TRANSP representation of passive shell and limiter (solid lines). Elements of PBX-M internal hardware (passive shell and indentation coil) are shown.

Fig. 5. Energy spectrum from multi-sightline charge exchange neutral analyzer from near-perpendicular view. Enhanced losses are seen at energies lower than 15 keV.

Fig. 6. Relevant terms of the thermal ion-power balance, top panel. Time evolution at $r/a = 0.5$. Shown are the ion heating power P_{ion}^{fast} , the ion-conduction loss P_{cond}^{ion} , the ion-electron exchange term Q_{ie} , the ion-convection loss P_{conv}^{ion} , and the time derivative of the ion stored energy $\dot{W}_{ion}$. The ion conduction is the dominant loss mechanism for the thermal ions. Electron power balance, bottom panel.

Fig. 7. Transport analysis assuming classical fast-ion losses. Time evolution of ion (χ_i^{CFIL}) and electron (χ_e^{CFIL}) diffusivities: increasing trace thicknesses correspond to minor radius $a/3$, $a/2$, and $2a/3$ respectively. Range bars are discussed in text. Staircase trace indicates neutral beam injector "on" times. Dotted (χ_i^{CFIL}) trace corresponds to T_i -data sensitivity analysis (see text).

Fig. 8. T_i and T_e profiles at different time point of interest: end of L-mode, quiescent H-phase, and MHD active H-phase. Data shown corresponds to TRANSP mapping of experimental data. Representative error bars are shown.

Fig. 9. Comparison of stored energy between TRANSP and FQ. Error bars shown are computed variances from five TRANSP analyses.

Fig. 10. Comparison of neutron rate between TRANSP and measured data.

Fig. 11. Transport analysis assuming enhanced fast-ion losses for times greater than 0.46 s. Time evolution of ion (χ_i^{EFIL}) and electron (χ_e^{EFIL}) diffusivities: increasing trace thicknesses correspond to minor radius $a/3$, $a/2$, and $2a/3$ respectively. Range bars are discussed in text. Staircase trace indicates neutral beam injector "on" times. Dotted (χ_i^{EFIL}) trace corresponds to T_i -data sensitivity analysis (see text).

$$\kappa = \frac{b}{a}$$

$$l = \frac{d}{2a + d}$$

$$\delta = \frac{c}{2a}$$

Fig. 1

Fig. 4

Fig. 5

L-MODE
 $P_{\text{abs}} = 2.3 \text{ MW}$

H-MODE
 QUIESCENT PHASE
 $P_{\text{abs}} = 4.2 \text{ MW}$

H-MODE
 MHD ACTIVITY
 $P_{\text{abs}} = 4.3 \text{ MW}$

FIG. 10

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