EFDA–JET–CP(07)01–13

D. Van Eester, E. Lerche, P. Mantica, A. Marinoni, A. Casati, G. Ericsson,
L. Giacomelli, C. Hellesen, A. Hjalmarsson, J. Källne, V. Kiptily,
S. Sharapov, M. Santala, T. M. Biewer, C. Giroud, K. Crombe, Y. Andrew,
J. Ongena, E. Joffrin, P. Lomas, R. Felton, F. Imbeaux, F. Ryter
and JET EFDA contributors*

Recent Experimental Results and Modeling of RF Heating of (^{3}He)-D JET Plasmas: RF as a Tool to Study Transport

Recent Experimental Results and Modeling of RF Heating of (^{3}He)-D JET Plasmas: RF as a Tool to Study

D. Van Eester[1], E. Lerche[1], P. Mantica[2], A. Marinoni[3], A. Casati[4], G. Ericsson[5],
L. Giacomelli[5], C. Hellesen[5], A. Hjalmarsson[5], J. Källne[5], V. Kiptily[6],
S. Sharapov[6], M. Santala[6], T. M. Biewer[7], C. Giroud[6], K. Crombe[6], Y. Andrew[6],
J. Ongena[1], E. Joffrin[4], P. Lomas[6], R. Felton[6], F. Imbeaux[4], F. Ryter[8]
and JET EFDA contributors*

[1] *Lab. for Plasma Physics-ERM/KMS, TEC partner, Brussels, Belgium*
[2] *Istituto di Fisica del Plasma, Assoc. Euratom-ENEA-CNR, Milano, Italy,*
[3] *CRPP-EPFL, Lausanne, Switzerland,*
[4] *CEA/DRFC Assoc. Euratom-CEA, Cadarache, France,*
[5] *TSL, Uppsala University, Uppsala, Sweden,*
[6] *Euratom-UKAEA Fus. Assoc., Culham Science Centre, United Kingdom, Oak Ridge National Laboratory,*
[7] *Oak Ridge, TN 37831, USA,*
[8] *IPP-MPG, Garching, Germany,*
** See annex of M. Watkins et al, "Overview of JET Results ",*
(Proc. 21st IAEA Fusion Energy Conference, Chengdu, China (2006).

Preprint of Paper to be submitted for publication in Proceedings of the
17th Topical Conference on Radio Frequency Power in Plasmas,
(Clearwater, Florida, USA, 7-9th May 2007)

ABSTRACT

D plasmas with ^{3}He minorities have sharp, thin ion-ion hybrid layers that enable to efficiently excite short wavelength branches that are subsequently damped by fairly well localized electron Landau and TTMP absorption. Depending on the minority concentration chosen, ion minority heating or electron mode conversion damping is dominant. Recent experiments have been devoted to the study of (^{3}He)-D JET plasmas. One aspect of those experiments - using RF heating as a tool - is the study of the response of the plasma to RF power modulation, allowing to examine the fate of the RF power and to diagnose particle and energy transport. The present paper gives a very brief summary of a subset of these experiments. The focus will largely but not exclusively be on understanding ITB physics. The adopted probing methods are more generally applicable, though.

INTRODUCTION AND MODELING

Transport studies require localized heat sources and rely on the effect of these heat sources being detected via detailed temperature (and in principle also density) response studies. This is typically done by modulating the auxiliary heating power, which causes the temperature to "break" $\partial T / \partial t_{pre} \neq \partial T / \partial t_{pre}$ post prepostevery time the power level is abruptly changed. In JET a modulation frequency of $\approx$ 20Hz of the RF power was used for electron transport studies. Ion transport studies not only require a lower modulation frequency ($\approx$ 6Hz) but also a more sophisticated analysis since their response is slower hence the simple "breaking" of the bulk ion temperature is not only mixed up by the indirect heating via the fast minority that is slowing down but the essentially linear behaviour is replaced by a saturation prior to and an exponential decay after the break (see e.g. [1] for an example).

Theoretical predictions reveal that - for typical JET conditions - optimal ^{3}He minority heating in D plasmas occurs at ^{3}H e concentrations of about 8% while electron "mode conversion" damping on short wavelength waves near the ion-ion hybrid layer requires X [^{3}He] $\approx$ 18%. As ^{3}He is fairly massive, it takes significant RF power levels to drive energetic ^{3}He tails. Hence plasmas containing ^{3}He minority species are optimal for doing transport studies for which "isolated" ion or electron heat sources and channels are desired. Because the ^{3}He tail temperatures remain modest, the drifts of these particles away from magnetic surfaces are small - at least when compared to those of fast H orbits - and hence the ion deposition profile is fairly localized. The mode conversion absorption profile is more localized still.

Three interesting experimental regimes can be distinguished for (^{3}He)-D plasmas: (1) the mode conversion regime which is optimal for performing electron heat studies, (2) the minority heating scheme which allows probing plasmas for ion transport and (3) the regime of very low ^{3}He concentrations during which RF power allows to trigger MHD activity through excitation of Alfven modes sapping energy from the RF heated unstable fast particle population(s). All 3 regimes have been examined in JET.

REAL TIME CONTROL OF THE ^{3}HE CONCENTRATION

To ensure the localized heat source does not move as a function of time, mode conversion heating relies on being able to freeze the ^{3}He concentration. Traditionally this has been done by constructing a feedback loop which ensures the ^{3}He gas injection modules are opened whenever the desired concentration falls under a predetermined value [2]. This requires an approximate expression for the 3He concentration which can be evaluated in real time during the discharge. Mantsinen proposed an elegant, yet powerful formula achieving this [3]: relying on the local charge neutrality and on the definition for Z_{eff}, Mantsinen worked out a formula to guess the ^{3}He concentration assuming the only plasma impurity is C, this being the case for scenarios not interacting violently with the wall and in which no impurities are purposely injected. For more extreme circumstances, the formula was generalized to include the effect of other impurities besides C. The key philosophy adopted is that the light emitted by a population is proportional to its density and so - provided the light intensity is only a weak function of other parameters - relative light intensities can be transformed into relative densities provided the proper proportionality factor is known.

RF POWER MODULATION AND TRANSPORT ANALYSIS PHILOSOPHY

A periodic modulation of the RF power yields a periodic variation of the temperature. Although RF power modulation is used in the first place to pin down the experimental heat deposition profile, the spreading through heat diffusion - an at first sight undesirable effect - is routinely used to probe the transport and find its diffusion characteristics by solving the heat and particle transport equations. These often are equations of the Braginskii type but with some extra freedom left by adding some empirical expression for the turbulence-driven diffusion. Making guesses of the local diffusivity and modifying the model's free parameters until a reasonable agreement between the experimental and theoretically predicted temperature response is obtained [4] allows to set apart heating and heat wave propagation. The philosophy of this approach can easily be sketched adopting a simple transport model: Assume heat can diffuse away from where it was applied and can be lost at a given rate. Then the energy density ε satisfies $\partial\varepsilon/\partial t = \partial/\partial x[\varkappa\partial\varepsilon/\partial x + V\varepsilon] - \varepsilon/\tau$. Imposing a periodic heat source, each of the decoupled temperature Fourier harmonics can be found individually. Provided the source is a delta function and without convection ($V = 0$), this yields a solution proportional to $\exp[-\alpha|x - x_o|]$ in which $\alpha = x - xo|]$ in which $\alpha = \sqrt{[1/\tau + in\omega]}/\varkappa$ [5]. Hence, for a source localized at a given position, both the amplitude and the phase of the energy response go through an extremum at the source. Away from the source the gradient is determined by the interplay between modulation, losses and diffusion. At high modulation frequency or high harmonics, the response mimics the shape of the heat source. The higher the diffusivity, the wider the spreading away from the source. When $\omega\tau >> 2\pi$ (more typical for electrons) losses play a minor role only and the temperature changes roughly linearly with time at a given power level; when $\omega\tau \approx 2\pi$ (more typical for ions) losses can no longer be neglected and the temperature has an exponential rather than a linear response to the RF power changes. Adjusting $\varkappa$, V and τ to bring the predicted response as close as possible to the experimental data yields the (profiles of the) unknown parameters.

PROBING ITBS USING RF POWER

Internal transport barriers (ITBs) are regions inside the plasma where the (ion and/or electron) temperature or density locally steepen. This steepening is accompanied by a poloidal shear flow (sometimes interpreted as a flow due to the fact that some mechanism evacuates fast particles, which yields the plasma setting up a radial current and electric field that - with the toroidal magnetic field component - produces a poloidally directed E × B flow). Extensive examination has revealed a deep relationship between the barriers and the q-profile [6]: when - typically due to Lower Hybrid preheating - a reversed q-profile is formed, the minimal q value decreases as the current penetrates. When q crosses rational values, more or less strong ITBs may be triggered at the location of the minimal q. The ITBs are particularly strong when q crosses integer values. Strong ITBs have been created at $q_{min} = 2$ and somewhat weaker ones further out at $q_{min} = 3$. MHD relaxation phenomena similar to sawteeth (although q commonly is well above 1) are typically accompanying the barriers.

In case RF heating creates fast particle populations, so-called Alfven "cascades" are triggered when qmin is rational, each mode satisfying nqmin = m. Because the time derivative of the Alfven frequency $\omega_{AC} = V_A k_{//}$ - with V_A the Alfven velocity and $k_{//} \approx (n - m/q_{min})/R_o$ the parallel wave number - changes as the time derivative of m/qmin and thus is proportional to the poloidal mode number m, the cascades' frequency increases as qmin decreases. When qmin is an integer, a "grand" cascade is formed: various modes share a same frequency when created and are then frequency separated at a rate proportional to the relative poloidal mode number. Cascades are excellent diagnostics for ITBs [7]: there is a 1-to-1 relation between the time ITBs are formed and the time cascades are appearing. Of course, as cascades necessitate sufficiently fast particles, they only exist when auxiliary heating is capable of creating an unstable subpopulation to excite them. Hence this accurate ITB "detection" tool is not always available. RF heating is commonly used to create the instrumental fast population. This is easier in a H minority than in a ^{3}He minority plasma, except when X [^{3}He] is very small.

To date, no theoretical models exist that satisfactorily describe transport in tokamaks. Lacking such models, empirical ones are often adopted. The critical gradient model was used to study the transport in JET [8]. This model describes how turbulence lifts transport well above the neoclassical level once the temperature gradient exceeds a threshold. During recent JET campaigns the determination of the characteristics of internal transport barriers was the main aim of the transport studies. Analysis of the temperature response revealed transport barriers are characterized by a tiny region from the ITB foot inward in which the heat diffusivity drops down an order of magnitude or more [4], [9]. It was shown that the improved confinement does not extend up to the core and that exotic transport phenomena (e.g. apparent convection leading to the maximal temperature response to a power modulation being displaced from the heat source) can occur [10].

A first analysis of experiments probing the plasma to find out what the dominant role of the auxiliary heating is by substituting neutral beam for dipole phased RF power (thus trying to answer the question whether - aside from the known role to slow down the current diffusion and thereby allowing to sustain the barrier longer - it is the energy or the momentum or torque input that matters) was inconclusive [11]: aside from the confirmation that the magnetic field structure and in particular the zero of the magnetic shear is more important than the auxiliary heating (as extensively studied, e.g. by Joffrin [6]), it turned out to be hard to significantly modify the nature of the internal transport barrier by applying different torques (different NBI power for a given NBI+RF power).

FAST PARTICLE POPULATIONS AND MHD ACTIVITY IN ITBS

For realistic RF power densities and reactor relevant particle densities, it is only possible to drive tails of energetic ^{3}He ions in JET when working at low ^{3}He concentrations. However, during the mode conversion experiments, with X [^{3}He] $\approx$ 18% during shots 69392 and 69393, the TOFOR “time of flight” neutron diagnostic [12] [13] observed an at first sight unexpected fast particle population.

This fast population was identified not as a ^{3}He but as a deuterium tail with an energy of more than 300keV. This is consistent with the information inferred from gamma rays, giving an estimate of the average D tail temperature of T_D = 400 ± 100keV for shot 69392; various peaks in the γ spectrum of these high X [^{3}He] shots arise from reactions requiring fast D (for similar results see e.g. [3]). Although the deuterium cyclotron layer was at the far high field side and thus thermal D ions are not expected to allow tail formation because of the limited power density, the 130keV D beam particles have a Doppler shift of about 0.4m. Due to this fast “preheated” population injected into the machine, D heating becomes an important ingredient of this scenario (consult [14] to get a flavor of the importance of the Doppler shift when RF heating a D beam population).

Without ^{3}He injection, the only ^{3}He coming into the plasma is the tiny fraction residing in and evacuated from the machine wall. Experiments aiming at exciting MHD modes driven by RF heated fast particle populations allowed fishbones, toroidal Alfven eigenmodes and Alfven cascades to be observed when X [^{3}He] was 1% or lower [15]. Gamma rays [16] with energies in the range $\approx 10 - 18$MeV testify for ^{3}He being RF heated and the reaction $D + {}^3He \rightarrow {}^5Li + \gamma$ (16.4MeV) taking place. A first assessment suggests ^{3}He tails of maximally 500keV were created. The carbon reaction ^{12}C(p, p’ ^{12}C reaction, producing 4.4MeV γ rays requires high energy protons. As the RF heating was not tuned to H, these energetic proton likely arises from the $D +^3 He \rightarrow {}^4 He(3.6MeV) + p(14.7MeV)$ reaction. Significantly reducing the RF power during intervals of a few hundred ms allows to identify the effect of the RF heating on the MHD activity: modes disappear or become much weaker when the RF heating level is reduced, in good agreement with expectation from theory predicting such modes rely on fast particle “current sources” for their excitation [17]. Both the number and the energy of lost fast ions [18] correlates with the RF power; the effect of the slowing down of the fast particles (fusion created protons) can clearly be observed on the lost ion time traces.

ACKNOWLEDGEMENTS

This work has been conducted under the European Fusion Development Agreement.

REFERENCES

[1]. E. Lerche et al., “Improved break-in-slope analysis for estimation of power dep. profiles in JET”, this conference

[2]. D. Van Eester et al., Proc. 15th Top. Conf. on RF Power in Plasmas, Wyoming, AIP 694, 66-73 (2003)

[3]. M. Mantsinen, Nuclear Fusion **44** (1), 33-46 (2004)

[4]. P. Mantica et al., Phys. Rev. Letters, **96**, 0950020 (2006)

[5]. D. Van Eester, Plasma Phys. Contr. Fusion **46**, 1675-1697 (2004)

[6]. E. Joffrin et al., Nuclear Fusion **43** 1167-1174 (2003)

[7]. S. Sharapov et al., Phys. Rev. Lett. **93**, 165001 (2004)

[8]. X. Garbet et al., Plasma Phys. Contr. Fusion **46**, 1351-1373 (2004)

[9]. A. Marinoni et al., Plasma Phys. Contr. Fusion **48**, 1469-1487 (2006).

[10]. A. Casati et al., “Critical temperature gradient signatures in heat propagation across Internal Transport Barrier in JET”, prepared for submission to Phys. Plasmas

[11]. N. Hawkes et al., “Ion Transport Barrier Formation with Low ExB Shear in JET”, to be presented at the 34th (Warsaw 2007) EPS conference

[12]. A. Hjalmarsson et al., Rev. Sci. Inst **74**, 1750-1752 (2003) and J. Kallne et al., “Advanced Neutron diagnostics for ITER Fusion Experiments”, 2004 Report EFDA-JET-CP(04)07-19.

[13]. C. Hellesen et al., “Measurement and analysis of the neutron emission from RF and NB heated JET D plasmas using the TOFOR spectometer”, and A. Hjalmarsson et al., “Neutron emission spectroscopy diagnosis of fast ions in RF heated D(^{3}He) plasmas at JET” both to be presented at the 34th (Warsaw 2007) EPS Conference

[14]. E. Lerche et al., “D maj. htg. in JET plasmas: ICRH modeling & analysis of RF power dep. profiles”, this conference

[15]. V. Kiptily, TF-M Mtg. talk 6/2/7 “MHD exp. with ^{3}He-minority ICRH: confinement, redistribution and ion losses”

[16]. V. Kiptily et al., Nuclear Fusion **42**, 999-1007 (2002)

[17]. T. Bergkvist et al., Nuclear Fusion **45**, 485-493 (2005)

[18]. D. Darrow et al., Rev. Sci. Instr. **77** 10E701 (2006)