nature portfolio

Peer Review File

Stable Deuterium-Tritium plasmas with improved confinement in the presence of energetic-ion instabilities

Editorial Note: Parts of this Peer Review File have been redacted as indicated to maintain the confidentiality of unpublished data.

REVIEWER COMMENTS

Reviewer #1 (Remarks to the Author):

Please see attachment.

Review "Stable D-T burning plasmas with improved confinement in the presence of energetic-ion instabilities" J. Garcia et al

The authors present new experimental results from JET during its last D-T campaign. The results may have significant implications for future D-T core plasma scenarios since these new experiments took care to produce a core plasma scenario more akin to ITER and SPARC: low torque, dominant electron heating, and a significant energetic-ion population. The analysis and modeling reveal an interesting synergy between the presence of non-thermalized energetic ion populations, magnetic instabilities, flow pattern creation and turbulent confinement properties. Based on this I recommend publication in Nature Comms because this insight is likely important in considerations of the details of burning plasma scenarios. Programmatically for magnetic fusion a significant result from JET in its last campaigns should also garner the wider scientific audience of Nature Comms because the next D-T fusion experiments are several years away.

However, I must insist that the authors modify the manuscript to clarify their narrative of the scientific insights gained by the work. More specifically the title, abstract and text of the manuscript create an impression that the D-T fusion, produced by having real tritium fuel used rather than just D, is the primary cause of the plasma behavior. This impression is not correct. By my estimate (see below) plasma gain Qp = P_fusion/P_external < 0.05 in the analyzed time window of #998961, which places it a factor of 100 away from a burning plasma regime, Qp>5, where self-heating from alphas dominate because the alpha heating is 100x less than the externally applied heating power. Therefore D-T fusion, alpha heating and fusion produced energetic-ions (i.e. the alphas) play effectively zero role in setting the performance of these discharges. The results are not about D-T fusion, but rather the use of ICRF heating to both produce dominant electron heating and a substantial energetic-ion population in a central location in the core, rather than using neutral beam injection which cannot produce these effect. By doing so the experiment has indeed created a proxy for energetic ions that would be present in a burning plasma. However, the actual effect of using tritium fuel is to improve the core energy confinement performance by the expected isotope mass scaling that has been a longtime empirical result. Indeed, this is proven by the authors on lines 160-161 who inform that D-D shots with same heating mix caused exactly the same set of magnetic instabilities, which are at the heart of the effects on confinement.

Therefore ,I ask that the authors make significant modifications to address this so that a general reader understands the fact that the experiment is a proxy of one effect, albeit an interesting one, for a burning plasma, but is not actually a burning plasma. Specifically bring forward the actual result about the synergistic loop described in the opening paragraph of this review and remove or clarify the remarks on the role of D-T or tritium. Furthermore ,there is no integrated modeling provided that shows in an actual burning plasma what would be the quantitative impact of this ion-flow-stability-turbulence. This is because that task is beyond our predictive capability since the strong interplay between the pressure profile and central heating that arises in an actual burning plasma (again 100x the amount of self-heating than in these shots). In a burning plasma the interplay between the heating source and the profiles is severe since the profiles are dominated by the power balance between alpha heating, varying like pressure squared, and the local profiles for whatever dominant turbulent regime will be present, almost certainly ITG. Indeed, this is why we are building burning plasma experiments in ITER and SPARC. Therefore, the direct line of the author's presented result to burning plasma relevance are not so strong as presented.

Thus my major feedback is that the authors remove the rhetoric (for lack of a better word) around D-T, burning plasma etc in the paper. Here are several examples in the manuscript.

The first one is in the title itself

Stable Deuterium-Tritium burning plasmas with improved confinement in the presence of energetic-ion instabilities.

This must be modified. Any casual reader would think this meant a burning plasma was studied.

In the introduction.

humanity. Energy produced by fusion reactions, in particular in tokamaks, is a promising path towards that goal. However, there is little experience with plasmas under conditions close to those expected in future fusion reactors, because it requires the fusion of Deuterium (D) and Tritium (T), while most of the experiments are currently performed in pure D. After more than

As pointed out the fusion of D-T has nothing to do with the result. The use of a different mass isotope is what has changed, but again that is well-established effect in tokamak confinement. Indeed if somehow one could construct proton (H) plasmas, plus the right ICRF heating profile to produced energetic ions, and then add D, one would get similar relative improvement.

Another example is here

reduction of energy losses with respect to D, has been found. Multiscale physics mechanisms critically determine the thermal confinement and the fusion power yield. These crucial achievements importantly contribute to the establishment of fusion energy generation as an alternative to fossil fuels.

In fact the fusion yield is <u>never</u> mentioned in the paper (it should be), so again a casual reader of the paper is led to believe these effects are playing a major role in the presented results. The second sentence is not directly relevant to the article's importance for fusion science.

On the other hand, the results obtained are not enough to provide a clear insight into how future energy-producing reactor plasmas are expected to behave. The reason is that in significant contrast to plasmas produced nowadays, formed almost exclusively by pure Deuterium (D), energy-producing plasmas will use Deuterium and Tritium (T) to produce 14.1 MeV neutrons and 3.5 MeV ^{4}He nuclei (alpha particles). The presence of T has been identified as a potential source of significant changes with respect to pure D plasmas, particularly in terms of turbulence or MHD characteristics [8] [9]. Furthermore, the presence of a small and yet very energetic population of alpha particles, which will provide the main self-heating mechanism through collisions to the thermal plasma, leads to conditions that are mostly unexplored and have been identified as potentially detrimental. The highly energetic

While not incorrect, misleading as to the results. The tritium mass isotope effect is rather modest ~20%, and D-T fusion has no role in the experiment.

Here are few more examples.

> to further clarify a safe and clear route toward the generation of efficient energy by means of fusion reactions. This is especially important for D-T plasmas. The presence of T, the generation of a high neutron rate at 14.1 MeV energy, or the presence of alpha particles, are all characteristics of D-T that are not present in ubiquitous pure-D discharges. Studying the impact of such differences is critical in order to properly characterize how D-T fusion reactors might behave. In particular, T can have a strong impact on confinement, impurity generation, and stability,

> plasmas, free of core impurity accumulation, while avoiding dangerous ELMs typical of standard H-modes and thus providing a stable plasma regime. These results confirm how crucial it is to perform experiments in D-T compared to D, as in addition to changes in confinement, burning D-T plasmas can be characterized by a strong nonlinear interplay between different plasma scales in the presence of highly energetic ions. This interplay can

I ask the authors to strongly modify or remove these kinds of statements, and make a more straightforward paper about the results. A key reason for this is the widely distributed character of Nature Comms articles which are read by many more that fusion and confinement experts. The excellent results of the paper on creating a more relevant proxy for burning plasma conditions stand on their own. In my opinion these scattered statements about D-T fusion and burning plasmas obscure the excellent results obtained by the team.

Specific technical comments

1. In the main article please provide more geometric parameters for plasma, R, a, etc
2. A table summarizing normalize and absolute parameters at timeslice would be helpful including power balance, gain, etc.
3. In Fig. 3 the authors claim that the lower continuum fluctuations below 100 kHz indicated better confinement. This is a highly qualitative statement at best since there is no radial correlation to this measurement.
4. Figure 4B…I think I'd much rather see the energetic protons ejected than the alphas since they are dominant.
5. Remove the section on burning plasma scenarios since I don't think it adds much to the paper.

[1]. Estimated plasma gain

Taken from the Fig. 1 at ~8.6 s

P_ICRF = 4.5 MW
P_NBI = 3.8 MW
P_fusion = 0.35 MW
P_alpha = 0.06 MW
V_loop ~ 0.19 V (estimated from Ip and <Te> ~ 2 keV, plasma resistivity ~ 1e-8 ohm-m)
P_ohmic ~ 0.35 MW
Qp ~ 0.04

P_external / P_alpha ~ 120

Reviewer #2 (Remarks to the Author):

The paper "Stable Deuterium-Tritium burning plasmas with improved confinement in the presence of energetic-ion instabilities" is devoted to the analysis of several D-T shots from the JET DTE2 campaign in comparison with similar D-D shots. Clarifying the features of D-T plasmas is an important and interesting task. However, the authors' consideration does not seem complete:
1) The authors analyze a few D-T shots. However it is not clear how representative and typical of D-T discharges in JET they are, including how far the characteristics of these discharges are from the boundaries of the operation region?
2) Authors wrote (page 3, line 107) that "up to 1 MW of fusion power is generated with only 2.4 MW of external ion heating. This type of plasma provides an integrated solution for future tokamak reactors…" However, Pfus=1 MW at Pheat=2.4 MW means Q=Pfus/Pheat~0.4 (and it is upper bound since Pheat is not total heating power, but only ion heating power). However Q=0.6 was reached in hot-ion mode in JET DTE1 campaign (see [1]). The latter regime seems to be more preferable for future reactor. It would be important to discuss the difference in Q values obtained in DTE1 and DTE2. What is the role of the transition from C wall to ILW?
3) D-T ratio scan is mentioned but experimental data are not well presented (page 5, lines 171-177): impact of T on plasma characteristics is not shown.
4) Core instabilities analysis. ITG mode is discussed as the major channel of transport losses. However in regimes with sufficient part of electron heating DTE mode or TEM can play a role. Authors should comment on this point.
5) Authors do not discuss q profile modification and its role in confinement properties. However confinement improvement - temperature profile peaking inside of rho~0.4 (see fig. 9) - can be caused by the q profile modification (i.e. magnetic shear decrease in vicinity of rational q surface). NTM 5/4 can change the magnetic shear near the q=1 surface and trigger change in confinement. Since the q profile can be a crucial factor in modification of transport it is important to show difference or similarity in q profile shapes in D-D and D-T discharges.
6) Experiments performed in DTE1 [1, page A42] showed that "global energy confinement is practically independent of isotopic mass". Authors of the presented paper on DTE2 conclude that "A clear reduction of energy losses by turbulence in D-T with respect to D leads to higher confinement plasmas…" It looks contradictory – contradiction between DTE1 and DTE2 results. Authors should comment on this point.
7) Section "Discussion" is to general. See for example the statements made in lines 384-392. Most of tasks were mentioned and discussed in [1] including clear electron heating by alpha-particles (see page A29). Authors should clearly specify what new points and conclusions were obtained from DTE2 in comparison to DTE1 and focus on differences between two experiments. It seems to be possible that the plasma-wall interaction can play a role (i.e. transition from C-wall to ILW).

[1] J Jacquinot and the JET team 1999 Plasma Phys. Control. Fusion 41 A13

Reviewer #3 (Remarks to the Author):

Major comments
This paper describes a new confinement improvement regime which is observed in D-T plasma and is associated with energetic ion driven instabilities. Unlike other confinement improvement, this new improved confinement can be achieved with low torque input. Achievement of improved confinement with low torque input is quite promising in the establishment of the future fusion reactor operation scenarios. Thus, I think the paper is worth publishing in the nature communications.
On the other hand, it is not clear what is the key mechanism for this improved confinement. So, I think the paper needs significant revise for the publication.

1. There are several candidates for explaining observed improvement. (1) isotope effect of bulk plasmas, (2)Difference of energetic-ion species, themselves, and (3) the difference of the effect on the instability drive by different energetic-ion species. Please explain the phenomena according to these view points.
2. It is not clear the function of energetic-ion instabilities on the improved confinement. Considering the explanation shown in the manuscript, similar improvement might be observed for D plasmas but not observed. Why? Zonal flow generations from the analysis by the FAR3D code is only discussed for D-T plasmas. Please show the analysis for D plasma.
3. In Fig.6C, the results of CGYRO is shown but is not clear the reduction of energy flux is due to the existence of energetic-ion or existence of energetic-ion driven instabilities. Which is important in the analysis of CGYRO?
Minor comments
1. Author mentions fusion output (P_fus). Is P_fus just the power produced by D-T fusion reaction or plasma heating power produced by the fusion reaction, i.e. alpha heating power. I assume it is former case, but it is a little confusing because author sometimes seem to compare the fusion power with external heating power. So, please indicate the meaning of fusion power more explicitly.
2. Author claims electron heating is dominant in the reported discharge but the actual electron and ion heating power is not shown. Please show them in addition to Fig.2. Because the kai_i shown in Fig.2C is larger than kai_e and T_i are similar to T_e in the region rho >0.4 in FIg.2, it looks ion heating is larger than electron heating. This contradicts to the authors' claim.
3. In page 5 between lines 175 and 177, the author claims that the reduction of kai_i,D-T/kai_e, D-T to 1 means reduction of ion thermal energy loss. Because it might happen when kai_e,D-T is increased, it is better to modify the expression of the sentence.
4. Author claims the low density fluctuation in the range below 150kHz as shown in Fig.3 supports the improved confinement described in Section 2. I think this claim is too strong. If you compare the density fluctuation in D-T plasmas of NBI case to NBI+ICRF case, the density fluctuation in this frequency range is similar but the H-factor shown in Fig.1 is smaller in the case of NBI.
5. Please includes the figures shown in the supplements if author needs to explain the phenomena. At least, the author needs to show the results of bi-coherence analysis in the main body of the manuscript, not in the supplement, because he mention it in the manuscript.
6. From Fig.4A, the inversion radius of n_alpha seems to be located inside the rho=0.25, where q=1 surface seems to locate. Why ? Please explain. Does FAR3D code consider the orbit of energetic-ions?
7. Why rho=0.31 is chosen for CGYRO simulation? Please explain.

We thank the referee for providing comments that indeed will improve the main message of the paper to the wide audience of Nature Communications.

We would like to highlight the following comment:

Based on this I recommend publication in Nature Comms because this insight is likely important in considerations of the details of burning plasma scenarios. Programmatically for magnetic fusion a significant result from JET in its last campaigns should also garner the wider scientific audience of Nature Comms because the next D-T fusion experiments are several years away.

We appreciate that the reviewer considers that our paper deserves publication in Nature Communications.

We now reply the to main comments by the reviewer.

The reviewer main criticism can be summarized in the following statement:

"Therefore ,I ask that the authors make significant modifications to address this so that a general reader understands the fact that the experiment is a proxy of one effect, albeit an interesting one, for a burning plasma, but is not actually a burning plasma."

Our intention with our paper was to show how a proxy for a burning plasma developed in JET D-T in order to characterize how a burning plasmas might behave in future tokamak fusion reactors. We tried to clarify this point throughout the paper first by highlighting the generic features of burning plasmas (high electron heating, low torque instabilities generated by energetic alphas) and then also clarifying that our experiment was not in those conditions, e.g. we clearly said that the instabilities were produced by the ICRF accelerated ions and in the conclusions we highlighted the necessity to perform experiments in conditions of dominant alpha particle heating, not like in the case of JET.

As a matter of fact our goal was not 100% successful and the message was not clear according to the reviewer. Then we agree on further clarifications and modifications of the paper as this is a very important point.

However, we would like to clarify that the fact that this experiment is performed in D-T provides not only information about the change from D to D-T but also important information about alpha particles themselves and therefore fusion yield. As shown in Figures 4 (A&B), significant alpha particle losses are detected with origin on fishbones and NTM even if the alpha particles are not in the origin of such instabilities. However, no losses are detected with origin on TAE. This is in line with the general assessment about alpha particle losses made for the high fusion power experiments carried out during DTE2. The underline physics is the non-linear interplay between energetic ions instabilities and alpha particles as shown by the FAR3D code. We believe that this information is essential to fully capture the message of the experiment shown In this paper, i.e. energetic ions perturbations might be beneficial for the plasma confinement but eventually lead to alpha particle losses, which may reduce the final fusion power yield. Very importantly, losses by ICRF accelerated protons and alpha particles are not similar in the presence of energetic ions instabilities, which reinforces the fact that D-T experiments are important to clarify the behavior of alpha particles. This point will be further clarified in one of the other points raised by the reviewer.

In order to clarify the previous points we have modified the paper as shown in the following.

The new title is

"Stable Deuterium-Tritium plasmas with improved confinement in the presence of energetic-ion instabilities"

The new abstract is

Providing stable and clean energy sources is a necessity for the increasing demands of humanity. Energy produced by Deuterium (D) and Tritium (T) fusion reactions, in particular in tokamaks, is a promising path towards that goal. However, there is little experience with plasmas formed by D-T mixtures, since most of the experiments are currently performed in pure D. After more than 20 years, the Joint European Torus (JET) has carried out new D-T experiments with the aim of exploring some of the unique characteristics expected in future fusion reactors, such as the presence of highly energetic ions in low plasma rotation conditions. A new stable, high confinement and impurity-free D-T regime, with reduction of energy losses with respect to D, has been found. Multiscale physics mechanisms critically determine the thermal confinement. These crucial achievements importantly contribute to the establishment of fusion energy generation as an alternative to fossil fuels.

The latest two paragraphs in the introduction are

The Joint European Torus (JET) tokamak [17], which is the only tokamak in the world capable of operating with T, has undergone a new experimental campaign in D-T, DTE2 [18], with the aim of providing solid evidence on the characteristics of D-T plasmas. A world record of fusion energy was produced in JET at the end of 2021 [19] by developing H-mode plasmas with ELMs. However, such an impressive result was obtained under conditions of high NBI power. In this paper, we describe DTE2 plasmas that, rather than maximizing the production of fusion energy, aim to capture other important characteristics expected in future fusion reactors, such as the simultaneous development of conditions with dominant total heating fraction transferred to the electrons, low input torque, and the triggering of Alfvén wave instabilities. Since the simultaneous development of plasmas with dominant alpha particle heating and low NBI input power is not possible at JET, the expected conditions in future fusion tokamak reactors were reproduced by using external heating with electromagnetic waves resonating at the ion cyclotron frequency (ICRF). In these conditions, low external torque is applied while generating ions in the MeV energy range and significant energetic ions related perturbations. These characteristics were not studied in the DTE2 fusion energy record, nor in the first D-T campaign in JET (DTE1)[9] or TFTR[8] in the 90s, since in both cases the maximization of the fusion power by using high NBI power was mostly explored and in such conditions plasmas with Ti/Te > 1 and high ion heating and rotation are obtained. Therefore, the study presented in this paper represents the first time that this path has been pursued in D-T plasmas.

We show that very good properties are achieved in terms of energy confinement and stability. The type of confinement expected in baseline reactor plasmas is obtained because of the better energy confinement in D-T with respect to the same conditions in D. In particular, for the electrons, the energy losses by transport are low, which allows temperatures of about 110 million K. For the ions, the core heat transport is significantly reduced in D-T compared to D when instabilities generated by the energetic ions are observed. This type of plasma provides an integrated solution for future tokamak reactors since, despite the development of an H-mode, deleterious ELMs are avoided. These results suggest improved energy confinement in future D-T plasma conditions.

The new conclusions are

The path towards commercial fusion reactors, although better understood in recent decades, still poses physics and technological uncertainties. The size, magnetic configuration, type of confinement, or power exhaust techniques expected in future tokamak devices are not fully established. Therefore, it is of fundamental importance to further clarify a safe and clear path toward the generation of efficient energy by means of fusion reactions. This is especially important for D-T plasmas. The presence of T, the generation of a high neutron rate at 14.1 MeV energy, or the presence of a significant population of alpha particles, are all characteristics of future fusion reactors in burning D-T plasmas that are not present in ubiquitous pure-D discharges. Studying the impact of such differences is critical in order to properly characterize how D-T fusion reactors might behave. In particular, T can have a strong impact on confinement, impurity generation, and stability, whereas alpha particles can lead to significant destabilization of magnetic perturbations and provide electron heating.

The JET tokamak has recently conducted a new D-T campaign after the first ones were developed at TFTR [8] and JET [9] in the 90's. In view of clarifying key physics elements that will characterize future D-T plasmas, several scientific directions have been explored. High fusion power generation has been obtained by using NBI heating, which is the main heating mechanism at JET. Other specific experiments have focused on several important topics that were not previously studied in D-T. A particular emphasis has been put on the exploration of some of the unique features expected in future D-T plasmas, i.e. simultaneous dominant electron heating, low rotation, and fully destabilized energetic ions instabilities. Since dominant electron heating by alpha particles is not possible in the JET tokamak at low rotation, the electron heating and high energetic particle generation, able to destabilize magnetic perturbations in stationary conditions, has been externally provided by using the maximum ICRF power available in DTE2.

A major result has been obtained suggesting that some reactor-relevant plasma conditions may be very beneficial. The development of large-scale energetic particle perturbations in the presence of highly energetic ions significantly reduces the conductive-convective energy losses driven by microturbulence in the plasma core leading to a good core energy confinement. The strong impact of zonal flows has been found to play a key role in the reduction of turbulent energy transport in the conditions explored. Importantly, at such low levels of energy losses, there is a clear asymmetry between T and D, since the presence of T significantly enhances the zonal flow activity and further reduces the energy losses by transport, resulting in a better global confinement in D-T compared to D.

Such results are obtained in a novel regime developed at JET, similar to the I-mode, consisting of the onset of a pedestal in the temperature while the density remains in L-mode and no damaging ELMs are detected. This new high confinement plasma regime is obtained close to the L-H transition threshold, and therefore requiring low input power. The presence of T is crucial also in the plasma edge, as at equivalent engineering parameters, a pedestal is developed in D-T but not in pure D.

Exploring a broad range of plasma conditions in present-day tokamaks is essential to evaluate how D-T plasmas might behave in the future. This is because the physics mechanisms expected to play a role in ITER and the future fusion reactor cannot be fully reproduced in an integrated way in existing tokamaks, and therefore specific studies must be performed. From this perspective, our studies complement the results obtained in DTE1 as they focus in different plasma regimes. DTE1 provided clear evidence of alpha heating, while differences in energy transport in D-T compared to D were weak and mostly with origin on the pedestal in H-mode plasmas heated with NBI. In DTE2, such results have been reproduced in H-mode plasmas when NBI is used as the main heating system and $T_i/T_e > 1$ [59][52]. However, our results significantly expand the knowledge about D-T by exploring some other conditions expected in future D-T plasmas that cannot be obtained in high NBI heated conditions. We show that close to the turbulence threshold in the presence of energetic ions instabilities, as expected in ITER [48], zonal flows can play a significant role and provide a route to lower core energy transport in D-T than in D. Importantly, the change from C-wall in DTE1, to Be and W wall and divertor in DTE2 has expanded the operational regime in which plasmas can be developed, significantly broadening the possibilities to perform experiments under conditions, notably at the plasma edge, not developed in DTE1 [44].

Our findings pave the way for a more economical and simpler design of tokamaks, confirming that nuclear fusion by means of magnetically confined D-T plasmas is a promising source of clean energy. However, further studies, such as compatibility with power exhaust capabilities and exploration at higher density and power, are required to fully qualify these plasmas as a solid route towards tokamak reactors. Furthermore, it is necessary to perform more detailed modeling activities to analyze multiscale effects involving energetic ions and plasma perturbations at different spatial and temporal scales, including the non-linear interaction of alpha particles with magnetic perturbations. The most important aspect is to develop plasmas in which, unlike in the JET results shown in this paper, alpha particle heating is dominant. To this end, experimental and modeling efforts in D-T including a significant population of alpha particles, as expected in ITER [60] or SPARC [61], are essential.

1. In the main article please provide more geometric parameters for plasma, R, a, etc

This is now included in the main article.

2. A table summarizing normalize and absolute parameters at timeslice would be helpful including power balance, gain, etc.

This is now included in the supplementary information.

3. In Fig. 3 the authors claim that the lower continuum fluctuations below 100 kHz indicated better confinement. This is a highly qualitative statement at best since there is no radial correlation to this measurement.

The statement has been changed to the following one

This supports the improvement in confinement for the thermal ions shown in Section 2 although further analyses are required in order to fully characterize turbulence reduction by means of radial correlation from reflectometry.

4. Figure 4B…I think I'd much rather see the energetic protons ejected than the alphas since they are dominant

This point raised by the reviewer goes back to the necessity of performing experiments in D-T rather than in pure D.

The FILD diagnostic in JET cannot distinguish by itself between high energy particle losses from alpha particles or protons. However the different characteristics of both species (isotropic distribution for alpha particles, specific pitch angle distribution for ICRF accelerated) allows to deduce that most of the high energy losses shown in this paper have origin on alpha particles rather than in ICRF accelerated ions for the discharge analyzed in this paper. Similar conclusions have been obtained analyzing other D-T discharges in the presence of ICRF, see e.g. reference [Ž. Štancar et al 2023 Nucl. Fusion 63 126058.]

Simulations with the code FAR3D also hint that alpha particle and ICRF accelerated ion losses can be quite different. In Figure 1 in this report, it is shown the ratio between alpha particles and protons in the initial phase of the simulations and during the fishbone instability development as obtained from FAR3D. Clearly, the alpha particle losses are much higher than the protons. We believe that this information is essential in order to properly qualify the impact of energetic ions instabilities in D-T plasmas and therefore we prefer to leave the figure as it is.

We have further clarified the text in the new version of the paper in order to make this point more clear.

[Redacted]

Figure 1. Ratio between the initial energetic ion population (alpha particles and trapped protons) and the one obtained during the simulation of the fishbone instability.

5. Remove the section on burning plasma scenarios since I don't think it adds much to the paper.

Unless there are problems with the length of the paper we would like to keep this section as it provides information about pure NBI plasmas and the difference with respect the ones developed with highly energetic ions.

We thank the reviewer for the important comments and for the suggestion to further clarify the difference between our results and those obtained in DTE1.

The paper “Stable Deuterium-Tritium burning plasmas with improved confinement in the presence of energetic-ion instabilities” is devoted to the analysis of several D-T shots from the JET DTE2 campaign in comparison with similar D-D shots. Clarifying the features of D-T plasmas is an important and interesting task. However, the authors' consideration does not seem complete:

We agree with the reviewer that clarifying D-T plasmas from DTE2 is important and we think that our paper goes in that direction. In the following, we will clarify all the points raised by the reviewer.

1) The authors analyze a few D-T shots. However it is not clear how representative and typical of D-T discharges in JET they are, including how far the characteristics of these discharges are from the boundaries of the operation region?

The scientific programme performed in DTE2 can be divided into two main groups. Those aiming at maximizing the fusion power, which largely used the maximum power available, and those exploring physics topics. Most of the discharges in both groups used as the main heating mechanism the NBI power as it is the heating system at JET delivering more power. In NBI heated plasmas, conditions of high ion heating, rotation and Ti/Te>1 are obtained, however those conditions are not fully representative of burning plasmas since they will be dominated by electron heating and low rotation. Therefore, some experiments were devoted to explore such plasma conditions in order to have a better assessment of potential differences between the common discharges performed in JET and those plasmas that will be developed in ITER.

The experiment shown in this paper belongs to the category of physics exploration of plasmas at high electron heating and low torque. In JET, the high electron heating can be obtained by using high ICRF and generating very energetic ions that heat the electrons but at the same time also destabilize energetic ion modes, as expected in ITER.

Therefore, this experiment requires maximum ICRF heating possible at JET during DTE2 (to minimize rotation) and minimum levels of H concentration for ICRF absorption (in order to maximize electron heating and energetic ions perturbations). It is worth to clarify that other experiments also explored alternative routes to the typical high NBI heating discharges and found, as it happens in our paper, significant differences in terms of confinement. This is the case of experiments on intrinsic rotation in ohmic plasmas (and hence with mostly electron heating), which found clear increase in thermal confinement with increasing mass [M.F.F. Nave et al 2023 Nucl. Fusion 63 044002], or strong isotope effects found in L-mode plasmas at low density in the presence of electron heating by NBI [T. Tala et al 2023 Nucl. Fusion 63 112012].

The results from these experiment indicate that D-T plasmas in conditions of high electron heating and low rotation can behave surprisingly good and be characterized by different plasma physics compared to those purely heated with NBI providing mostly ion heating.

2) Authors wrote (page 3, line 107) that "up to 1 MW of fusion power is generated with only 2.4 MW of external ion heating. This type of plasma provides an integrated solution for future tokamak reactors…" However, Pfus=1 MW at Pheat=2.4 MW means Q=Pfus/Pheat~0.4 (and it is upper bound since Pheat is not total heating power, but only ion heating power). However Q=0.6 was reached in hot-ion mode in JET DTE1 campaign (see [1]). The latter regime seems to be more preferable for future reactor. It would be important to discuss the difference in Q values obtained in DTE1 and DTE2. What is the role of the transition from C wall to ILW?

The input power quoted in the paragraph, 2.4MW, in the ion heating part of the total power, ~8MW. This was done is order to demonstrate that with small fraction of ion heating the fusion power can be high. However, we recognize that the statement can be confusing and therefore we have removed it.

3) D-T ratio scan is mentioned but experimental data are not well presented (page 5, lines 171-177): impact of T on plasma characteristics is not shown.

The results and figures for the D-T ratio scan are included now in the supplementary information. We prefer to show the case of the 50%-50% ratio in the main paper, as it is the mixture expected in ITER and the fusion reactor, and to provide further evince at different mixture in the supplementary information to avoid too many cases discussed in the main text.

4) Core instabilities analysis. ITG mode is discussed as the major channel of transport losses. However in regimes with sufficient part of electron heating DTE mode or TEM can play a role. Authors should comment on this point.

Linear simulations up to the Electron Temperature Gradient (ETG) scales were performed as shown in figure 1 in this report for all the cases included in the new version of the paper. The growth rate of the ETG mode peaks at $k_y\rho_s$=30 with $[(\gamma\ a/c_s)/(k_y\rho_s)]_{peak} = 0.28$. The growth rate of the ITG mode peaks at $k_y\rho_s = 0.5$ with $[(\gamma\ a/c_s)/(k_y\rho_s)]_{peak} = 0.39$, which is much larger than the ratio for the ETG mode. This indicates that multiscale transport is unlikely to be significant [Staebler et al., NF 56, 066046 (2017), Creeley et al., PPCF 61, 085022]. Multiscale simulation capturing both fast ion modes and ETG is very computationally challenging due to extreme spatial resolution requirements and thus beyond the scope of this work. However, for the case without fast ions, preliminary multiscale simulations capturing both the ion and electron gyroradius scales indicate that the nonlinear ETG transport is suppressed by the ion-scale fluctuations. This is consistent with previous work that showed that, when significant ion-scale (ITG) transport is present, electron-scale transport is often reduced by ion-scale fluctuations through nonlinear mode-mode interaction and zonal flows [Candy et al., PPCF 49, 1209].

[Redacted]

Figure 1. Growth rate obtained in linear CGYRO simulations for the cases considered in this paper. For $k_y\rho_s>1$ ETG modes are obtained.

The following text has been added to the new version of the paper:

Regarding turbulence in the ETG scales, multiscale simulation capturing both fast ion modes and ETG is very computationally challenging due to extreme spatial resolution requirements and thus beyond the scope of this work. However, for the case without energetic ions, preliminary multiscale simulations capturing both the ion and electron gyroradius scales indicate that the nonlinear ETG transport is suppressed by the ion-scale fluctuations.

5) Authors do not discuss q profile modification and its role in confinement properties. However confinement improvement - temperature profile peaking inside of rho~0.4 (see fig. 9) - can be caused by the q profile modification (i.e. magnetic shear decrease in vicinity of rational q surface). NTM 5/4 can change the magnetic shear near the q=1 surface and trigger change in confinement. Since the q profile can be a crucial factor in modification of transport it is important to show difference or similarity in q profile shapes in D-D and D-T discharges.

A very dedicated analysis was carried out in order to validate the q profile used to perform the simulations with the different codes used in this paper since the q profile plays a key role to properly evaluated MHD activity and turbulence transport. In figure 2, in this report, the q profile obtained from TRANSP for the D-T discharge 99896 is shown together with MHD markers for the q=1 and q=4/3 locations. The q profile from TRANSP compares well with the MHD markers, providing confidence that the simulations performed using this q profile are correct.

In the same figure, we have added the q profile obtained from TRANSP for the D discharge 100871. Clearly, the q profile is very similar to the D-T case. Further evidence is obtained by observing the type of magnetic spectrum obtained for both discharges, which is very similar as shown in figure 3 in this report, indicating that there are not significant differences between the q profile in both discharges.

The discussion about the q profile has been expanded in the Methods section by including Figure 2.

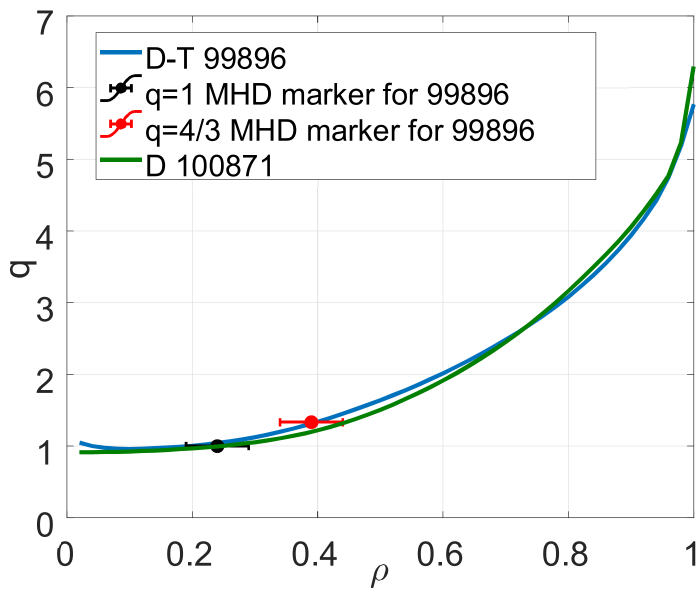
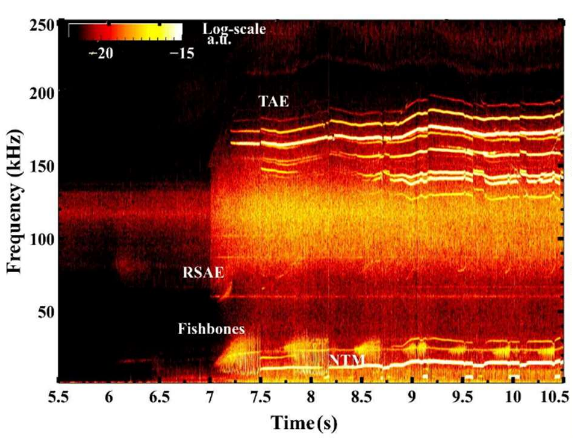


Figure 2. Comparison between the q profile obtained from TRANSP for the D-T discharge 99896 and the MHD markers for q=1 and q=3/2. The q profile for the discharge D 100871 from TRANSP is also added for comparison.



[Redacted]

Figure 3. Comparison between the magnetic spectrogram of the D-T discharge 99896 (left) and its counterpart in D 100871 (right).

6) Experiments performed in DTE1 [1, page A42] showed that "global energy confinement is practically independent of isotopic mass". Authors of the presented paper on DTE2 conclude that "A clear reduction of energy losses by turbulence in D-T with respect to D leads to higher confinement plasmas…" It looks contradictory – contradiction between DTE1 and DTE2 results. Authors should comment on this point.

The reviewer is raising a very important point that we did not sufficiently clarify. The type of plasma analyzed in this paper is obtained in conditions not explored in DTE1. First, the electron heating was maximized and rotation minimized by using the maximum ICRF power possible and reducing the NBI power. In such conditions a significant amount of energetic ion modes were obtained and very low core transport was developed. Second, the transition to H-mode was done at the low-density branch, which allowed to develop a new plasma regime at JET with no H-mode for the density but a clear pedestal for the temperature.

All these novel conditions were developed in DTE2 with the aim of mimicking potential plasma regimes in ITER and DEMO reactor conditions.

The fact that a strong isotope effect, different to DTE1, is obtained in this new conditions might not be a surprise as this was not previously explored. Actually, indication of significant isotope effects in core transport driven by turbulence were already hinted in numerical investigations for D-T plasmas in conditions of low transport and strong zonal flow activity [J. Garcia et al 2017 Nucl. Fusion 57 014007] [J Garcia et al 2022 Plasma Phys. Control. Fusion 64 054001], precisely as obtained in these JET results. It is important to clarify that results similar to those obtained in DTE1 in terms of plasma confinement dependence on the isotope were obtained in DTE2 when performing experiments in H-mode type-I ELMs regime plasmas heated purely with NBI [P.A. Schneider et al 2023 Nucl. Fusion 63 112010]. This confirms that the role of isotope can be different different in different plasmas conditions, and highlight the necessity to explore conditions close to those expected in burning plasmas.

In conclusion, the results are not contradictory; they are just obtained in different plasma conditions.

This is clarified in the new version of the conclusions in the paper.

7) Section "Discussion" is to general. See for example the statements made in lines 384-392. Most of tasks were mentioned and discussed in [1] including clear electron heating by alpha-particles (see page A29). Authors should clearly specify what new points and conclusions were obtained from DTE2 in comparison to DTE1 and focus on differences between two experiments. It seems to be possible that the plasma-wall interaction can play a role (i.e. transition from C-wall to ILW).

The new conclusions are the following ones:

The path towards commercial fusion reactors, although better understood in recent decades, still poses physics and technological uncertainties. The size, magnetic configuration, type of confinement, or power exhaust techniques expected in future tokamak devices are not fully established. Therefore, it is of fundamental importance to further clarify a safe and clear path toward the generation of efficient energy by means of fusion reactions. This is especially important for D-T plasmas. The presence of T, the generation of a high neutron rate at 14.1 MeV energy, or the presence of a significant population of alpha particles, are all characteristics of future fusion reactors in burning D-T plasmas that are not present in ubiquitous pure-D discharges. Studying the impact of such differences is critical in order to properly characterize how D-T fusion reactors might behave. In particular, T can have a strong impact on confinement, impurity generation, and stability, whereas alpha particles can lead to significant destabilization of magnetic perturbations and provide electron heating.

The JET tokamak has recently conducted a new D-T campaign after the first ones were developed at TFTR [8] and JET [9] in the 90's. In view of clarifying key physics elements that will characterize future D-T plasmas, several scientific directions have been explored. High fusion power generation has been obtained by using NBI heating, which is the main heating mechanism at JET. Other specific experiments have focused on several important topics that were not previously studied in D-T. A particular emphasis has been put on the exploration of some of the unique features expected in future D-T plasmas, i.e. simultaneous dominant electron heating, low rotation, and fully destabilized energetic ions instabilities. Since dominant electron heating by alpha particles is not possible in the JET tokamak at low rotation, the electron heating and high energetic particle generation, able to destabilize magnetic perturbations in stationary conditions, has been externally provided by using the maximum ICRF power available in DTE2.

A major result has been obtained suggesting that some reactor-relevant plasma conditions may be very beneficial. The development of large-scale energetic particle perturbations in the presence of highly energetic ions significantly reduces the conductive-convective energy losses driven by microturbulence in the plasma core leading to a good core energy confinement. The strong impact of zonal flows has been found to play a key role in the reduction of turbulent energy transport in the conditions explored. Importantly, at such low levels of energy losses, there is a clear asymmetry between T and D, since the presence of T significantly enhances the zonal flow activity and further reduces the energy losses by transport, resulting in a better global confinement in D-T compared to D.

Such results are obtained in a novel regime developed at JET, similar to the I-mode, consisting of the onset of a pedestal in the temperature while the density remains in L-mode and no damaging ELMs are detected. This new high confinement plasma regime is obtained close to the L-H transition threshold, and therefore requiring low input power. The presence of T is crucial also in the plasma edge, as at equivalent engineering parameters, a pedestal is developed in D-T but not in pure D.

Exploring a broad range of plasma conditions in present-day tokamaks is essential to evaluate how D-T plasmas might behave in the future. This is because the physics mechanisms expected to play a role in ITER and the future fusion reactor cannot be fully reproduced in an integrated way in existing tokamaks, and therefore specific studies must be performed. From this perspective, our studies complement the results obtained in DTE1 as they focus in different plasma regimes. DTE1 provided clear evidence of alpha heating, while differences in energy transport in D-T compared to D were weak and mostly with origin on the pedestal in H-mode plasmas heated with NBI. In DTE2, such results have been reproduced in H-mode plasmas when NBI is used as the main heating system and $T_i/T_e > 1$ [59][52]. However, our results significantly expand the knowledge about D-T by exploring some other conditions expected in future D-T plasmas that cannot be obtained in high NBI heated conditions. We show that close to the turbulence threshold in the presence of energetic ions instabilities, as expected in ITER [48], zonal flows can play a significant role and provide a route to lower core energy transport in D-T than in D. Importantly, the change from C-wall in DTE1, to Be and W wall and divertor in DTE2 has expanded the operational regime in which plasmas can be developed, significantly broadening the possibilities to perform experiments under conditions, notably at the plasma edge, not developed in DTE1 [44].

Our findings pave the way for a more economical and simpler design of tokamaks, confirming that nuclear fusion by means of magnetically confined D-T plasmas is a promising source of clean energy. However, further studies, such as compatibility with power exhaust capabilities and exploration at higher density and power, are required to fully qualify these plasmas as a solid route towards tokamak reactors. Furthermore, it is necessary to perform more detailed modeling activities to analyze multiscale effects involving energetic ions and plasma perturbations at different spatial and temporal scales, including the non-linear interaction of alpha particles with magnetic perturbations. The most important aspect is to develop plasmas in which, unlike in the JET results shown in this paper, alpha particle heating is dominant. To this end, experimental and modeling efforts in D-T including a significant population of alpha particles, as expected in ITER [60] or SPARC[61], are essential.

We thank the reviewer for the important and constructive comments that are very helpful to clarify the paper.

Major comments

This paper describes a new confinement improvement regime which is observed in D-T plasma and is associated with energetic ion driven instabilities. Unlike other confinement improvement, this new improved confinement can be achieved with low torque input. Achievement of improved confinement with low torque input is quite promising in the establishment of the future fusion reactor operation scenarios. Thus, I think the paper is worth publishing in the nature communications.

We thank the reviewer for supporting this paper to be published in Nature Communications.

On the other hand, it is not clear what is the key mechanism for this improved confinement. So, I think the paper needs significant revise for the publication.

In the following, we are going to clarify the points raised by the reviewer.

1. There are several candidates for explaining observed improvement. (1) isotope effect of bulk plasmas, (2)Difference of energetic-ion species, themselves, and (3) the difference of the effect on the instability drive by different energetic-ion species. Please explain the phenomena according to these view points.

The improved confinement observed in the plasmas shown in this paper have several potential origins as the reviewer correctly pointed out. Due to space limitations we did not fully clarify the differences between D and D-T but following the referee's comments we are including a more detail discussion in the revised version of the paper.

As discussed in the initial version of the paper, there are several reasons behind the good confinement obtained in these D-T plasmas. The first one is an increase of zonal flow activity when considering highly energetic ions as obtained in both gyrofluid and gyrokinetic simulations. Specifically, it is obtained that the intensity of zonal flow increases with the fast ion perturbation intensity, which directly points out that it is the energetic ions driven perturbations the ones that control the thermal heat transport by a coupling to zonal flows. The previous explanation does not preclude a potential direct impact of the energetic ions by themselves on the plasma confinement. In order to disentangle these effects, further simulations have been performed with CGYRO as shown in Figure 1 of this report.

Two extra simulations have been performed. They are identical to the one with energetic ions but changing just one parameter in each simulation in order to stabilize the Alfvén Mode while keeping the energetic ions as an active specie in CGYRO. In one simulation the value $R/L_{TFI}=0$ is chosen and in another one the value of the energetic ion energy is reduced four times down to $T_{FI}/T_e=5.25$. As shown in Figure 1, in the linear simulations the Alfvén Mode at low k_y is stabilized in both cases, which leads to very similar spectrum compared to the case without energetic ions in that k_y region. However, the k_y spectrum in the region with γ_{max} is nearly identical to the standard case with energetic ions. With this setting, it is possible to decouple the effects of the energetic ions by themselves and the energetic ion modes and importantly, this is done for two different ways of destabilizing the energetic ion mode.

Non-linear simulations, shown in Figure 1, show that the energetic ions by themselves have some stabilizing effect on the thermal fluxes as a consequence of the lower γ_{max} when energetic ions are considered in the simulations and the Alfvén Eigenmode is not present. However, it is demonstrated that the only way to match the energy fluxes from TRANSP is considering the standard CGYRO case with energetic ions in which the Alfvén Mode is destabilized.

Therefore, we conclude that the presence of an Alfvén Mode is necessary to recover the low fluxes from TRANSP at the radial location selected.

Regarding the influence of Tritium in the previous mechanism, an extended explanation will be given in the next point.

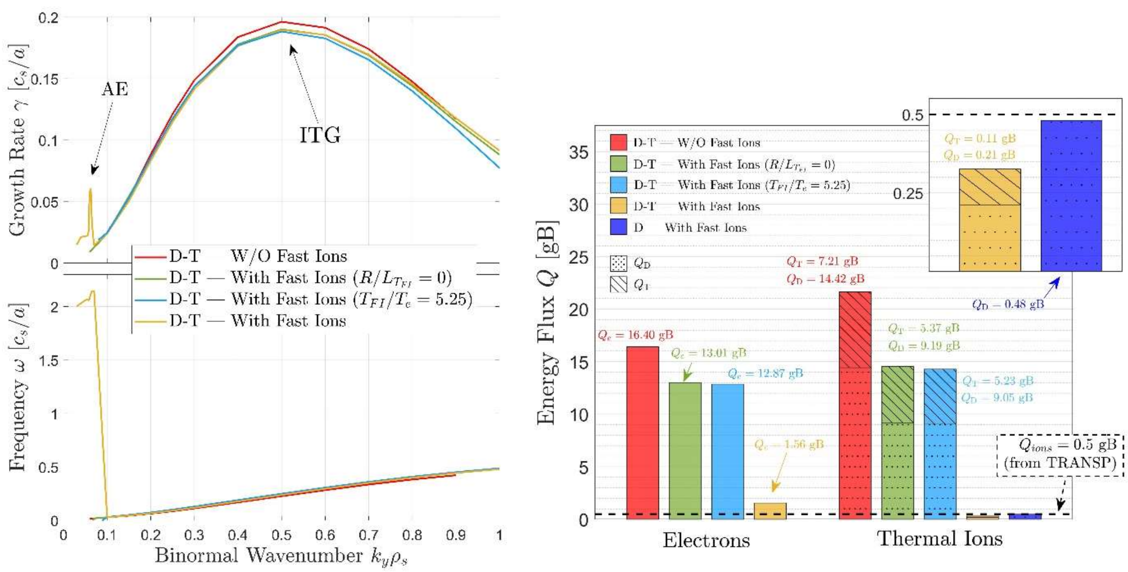


Figure 1. Growth rate and frequency from linear simulations performed with CGYRO with and without energetic ions. In the case with energetic ions, two extra cases are considered with R/L_{TFI}=0 and with T_{FI}/T_e=5.25. In both cases the high-frequency mode is stabilized (a). Thermal fluxes for electrons and ions for the four D-T cases considered (b).

The following text has been added to the new version of the paper:

Two extra simulations with CGYRO were performed to reveal the physics mechanism by which turbulent transport is strongly reduced in the presence of energetic ions. In both cases, the aim is to keep the energetic ions in the simulations but to stabilize the energetic ion mode at low ky by assuming either $a/L_{Ti} = 0$ or by reducing the energy of the energetic ions four times with respect to the standard case, down to $T_{FI} /T_e = 5.25$ as shown in Fig. 6 (A and B). As shown in Fig. 6(C), the presence of energetic ions without an energetic ion mode has some stabilizing effect on the thermal fluxes, but the matching of experimental fluxes is only obtained when the energetic ion mode is destabilized

2. It is not clear the function of energetic-ion instabilities on the improved confinement. Considering the explanation shown in the manuscript, similar improvement might be observed for D plasmas but not observed. Why? Zonal flow generations from the analysis by the FAR3D code is only discussed for D-T plasmas. Please show the analysis for D plasma.

As described in point 1, the high impact of zonal flows when the energetic driven instabilities are destabilized can explain the core heat transport reduction found in this paper. Such a mechanism indeed also applies to pure D plasmas for which it is found that confinement in the presence of highly energetic ions and instabilities is higher than in pure NBI conditions, H98(y,2)~0.65 with NBI and H98(y,2)~0.9 with NBI+ICRF. The CGYRO simulations described in point 1, figure 1, capture this trend as pure D simulations also show very low levels of heat transport when just changing T by D in the simulation and the Alfvén Mode is destabilized. However, the presence of T enhances this effect as also shown in figure 1, in which the total ion thermal heat flux in D-T is significantly lower than in D.

The reason for the lower core transport in D-T compared to D is the strongest generation of zonal flows by the energetic ions instabilities in the presence of T. In order to illustrate this point, we include the pattern of zonal flows obtained in FAR3D in the case of pure D plasma and compare to the previous figure, which was only shown in D-T. As shown in figure 2 in this report, clearly, when comparing the zonal flow activity in D-T and D when considering a fast ion energy of 1MeV (in both cases energetic ion instabilities are present) the intensity of zonal flow is stronger in the D-T case.

The higher impact of zonal flows in the presence of T was hinted in gyrokinetic numerical studies for ITER D-T plasmas in conditions of low turbulence when it is close to turbulence threshold [J. Garcia et al 2017 Nucl. Fusion 57 014007] [J Garcia et al 2022 Plasma Phys. Control. Fusion 64 054001]. In the proximity to threshold, it is well-known that zonal flows have a strong impact on the self-regulation mechanism of turbulence in plasmas, therefore it is not a surprise that the higher impact of zonal flows with T is particularly efficient close to threshold. In the JET case analyzed, turbulence is indeed very low, close to threshold, so reproducing conditions in which the stronger impact of zonal flows with T can be obtained. This is a new type of plasma regime uniquely explored in DTE2.

Importantly, the presence of T also leads to an improved confinement in the plasma edge as a temperature pedestal is observed in D-T, which is not observed in D. Therefore, the global confinement is significantly improved in D-T compared to pure D.

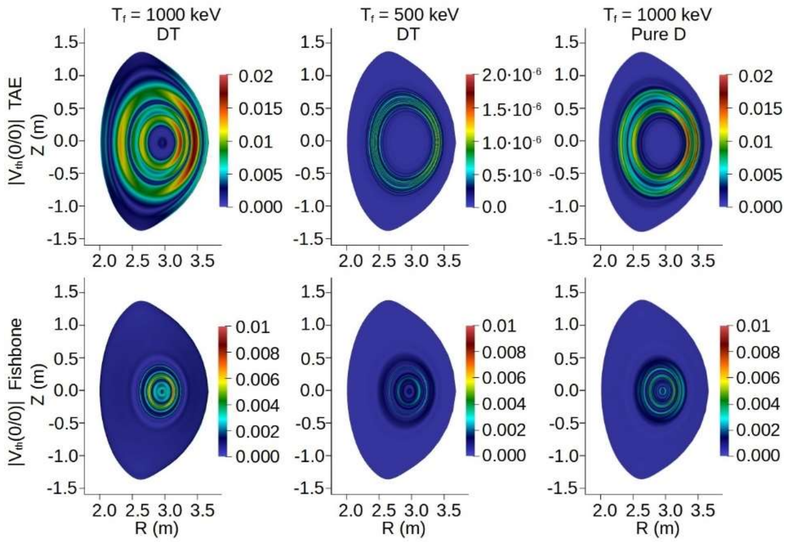


Figure 2. Zonal flow pattern from FAR3D for the D-T cases and comparison to pure D. The zonal flow intensity is stronger for DT than in D at the same energetic ion energy.

The following text has been added to the new version of the paper:

As shown in Fig.5(E and F), although the generation of zonal flow by fishbone and TAE is also present in pure D, the intensity of zonal flow is lower than in D-T, which could explain the lower turbulent transport found in D-T compared to D, as hinted previously in numerical studies performed in D-T plasmas when turbulent transport is close to threshold [43][44].

3. In Fig.6C, the results of CGYRO is shown but is not clear the reduction of energy flux is due to the existence of energetic-ion or existence of energetic-ion driven instabilities. Which is important in the analysis of CGYRO?

This subject has been discussed in point 1. We have shown that the energetic ion mode is a key point explaining the transport reduction in D-T plasma.

Minor comments

1. Author mentions fusion output (P_fus). Is P_fus just the power produced by D-T fusion reaction or plasma heating power produced by the fusion reaction, i.e. alpha heating power. I assume it is former case, but it is a little confusing because author sometimes seem to compare the fusion power with external heating power. So, please indicate the meaning of fusion power more explicitly.

The reviewer is right, we mean the power produced by D-T fusion reactions. We have clarified this in the new version of the paper.

"In terms of power produced by D-T fusion reactions, Pfus ~ 0.5 MW was obtained"

2. Author claims electron heating is dominant in the reported discharge but the actual electron and

ion heating power is not shown. Please show them in addition to Fig.2. Because the kai_i shown in Fig.2C is larger than kai_e and T_i are similar to T_e in the region rho >0.4 in FIg.2, it looks ion heating is larger than electron heating. This contradicts to the authors' claim.

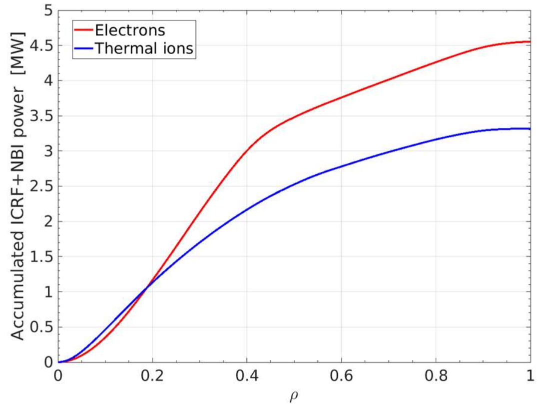


Figure 3. Radial distribution of the accumulated ICRF+NBI power as obtained from the TRANSP code.

This is an important point. The accumulated total ICRF+NBI power, as obtained from TRANSP, is shown in figure 3 in this report. The total electron heating sharply surpasses ion heating at ρ>0.2. The reviewer mentions that kai_i is higher than kai_e for ρ>0.4 but this is not related to the fact that there is more ion heating but rather there is a flattening of Ti in the region 0.4<ρ<0.6 which leads to an increase of kai_i compared to kai_e.

The figure is included in the new version of the paper in Figure 1.

3. In page 5 between lines 175 and 177, the author claims that the reduction of kai_i,D-T/kai_e, D-T to 1 means reduction of ion thermal energy loss. Because it might happen when kai_e,D-T is increased, it is better to modify the expression of the sentence.

The discussion about plasma with higher T is included now in the supplementary information. Clearly it is shown that with high T concentration kai_i,D-T/kai_e, D-T~1 but kai_e,D-T is as low as in the case of the discharge 99896.

4. Author claims the low density fluctuation in the range below 150kHz as shown in Fig.3 supports the improved confinement described in Section 2. I think this claim is too strong. If you compare the density fluctuation in D-T plasmas of NBI case to NBI+ICRF case, the density fluctuation in this frequency range is similar but the H-factor shown in Fig.1 is smaller in the case of NBI.

The reviewer is raising an important point. Indeed the fluctuation levels with only NBI and with NBI+ICRF are similar, however the case with ICRF has 4.5MW more power than with only NBI. In tokamak plasmas, it has been reported that the external input power causes confinement degradation because turbulence increases with power. This is the reason why in the IPB98(y,2) scaling the confinement time dependence on the input power scales as $P^{-0.69}$. However, in the D-T discharge 99896, turbulence does not increase with the external input power. In terms of H98(y,2) factor, it means that the confinement in the discharge 99896 is not degraded with external input power as expected from the IPB98(y,2) scaling.

We have performed further analyses including a late phase of the discharge 99896 with only ICRF power ~4.5MW. Although in this phase the power is not exactly the same as in the only NBI phase, which is ~3.5MW, it provides a better comparison about the total level of fluctuations. As shown in Figure 4, the level of fluctuations at ρ~0.35 with only ICRF is lower than with only NBI, even in the presence of Alfvén Modes when the ICRF is used. This confirms the interpretation of reduced turbulence in the presence of energetic ions and destabilized Alfvén Modes.

[Redacted]

Figure 4. Density fluctuation level as obtained from reflectometry at ρ ~ 0.35. The black D-T curve with only ICRF power is added in black.

We have modified the sentence regarding this point as follows:

This supports the improvement in confinement for the thermal ions shown in Section 2 although further analyses are required in order to fully characterize turbulence reduction by means of radial correlation from reflectometry.

5. Please includes the figures shown in the supplements if author needs to explain the phenomena. At least, the author needs to show the results of bi-coherence analysis in the main body of the manuscript, not in the supplement, because he mention it in the manuscript.

The figure has been included in the new version of the paper together with an explanation.

"However, nonlinear mode-mode interactions are at the origin of some of these fluctuations. This is demonstrated by performing a mode-mode bi-coherence analysis [34]. In particular, a nonlinear interplay between high-frequency TAE and low-frequency NTM is detected, as shown in Fig. 3. In particular, toroidal mode numbers n = 1 and n = 2 among other interactions are a result of such nonlinear interplays (this is shown in detail in the supplementary information)"

6. From Fig.4A, the inversion radius of n_alpha seems to be located inside the rho=0.25, where q=1

surface seems to locate. Why ? Please explain. Does FAR3D code consider the orbit of energetic-ions?

The high drop in the alpha particle density obtained in FAR3D is a consequence of the alpha particle losses driven by the fishbone instability. The fishbone instability is located inside q=1 as shown in figure 4(a) in the manuscript, and that is the reason why beyond q=1 no losses are obtained in FAR3D. Importantly to clarify, FAR3D does not simulate the NTM which also leads to alpha losses as shown experimentally in figure 4(b).

FAR3D indeed includes the orbit of energetic-ions.

The following text has been added to the new version of the paper:

It is found with FAR3D that alpha particles do not destabilize any perturbation due to their low density, however, nonlinear interplay with fishbones, located inside q=1 at $\rho \sim 0.25$, can induce radial transport and losses of alpha particles, partially depleting the plasma axis of such particles, as shown in Fig.4A.

7. Why rho=0.31 is chosen for CGYRO simulation? Please explain.

We have chosen that radial location because it is beyond the sawtooth inverse radius and it is a location in which TAE is detected. Therefore, it is a good location for CGYRO simulations to show the impact of Alfvén Modes on confinement.

The following text has been added to the new version of the paper:

Local simulations are performed at $\rho = 0.31$, as it is beyond the inverse radius of the sawtooth and is a location in which TAE is detected.

REVIEWERS' COMMENTS

Reviewer #1 (Remarks to the Author):

I thank the authors for addressing my concerns.

I have no further comments,

Reviewer #2 (Remarks to the Author):

The authors corrected the article in accordance with the comments. Article may be published.

Reviewer #3 (Remarks to the Author):

Most of the modification done by the authors are quite good. I think the paper is almost ready for publiaction except a following point.
1. In section 3, the authors pointed out that the EP driven mode plays an important role for core confinement improvement through Zonal Flow creation and supression of turbulences using the combined results of CGYRO calculation (Fig.6) and FAR3D (Fig.5). Considering the fact that the ITG growth rates shown in Fig.6(A) are almost the same, I assume author wants to claim that the damping effect on turbulence by ZF is significant. Because the reduction of energy flux in D-T with Fast Ions are shown in Fig.6(C) by yellow-bar, I assume the reducition in turbulence intensitisy should be also observed in CGYRO simulation if the author's claim is correct. So, please show the turbulence intensity by CGYRO calculation in Fig.6. This will be more direct explanations for author's claim.

We appreciate the support of the referee and the good comments that have indeed improved the paper.

Regarding the latest referee's comment:

"In section 3, the authors pointed out that the EP driven mode plays an important role for core confinement improvement through Zonal Flow creation and suppression of turbulences using the combined results of CGYRO calculation (Fig.6) and FAR3D (Fig.5). Considering the fact that the ITG growth rates shown in Fig.6(A) are almost the same, I assume author wants to claim that the damping effect on turbulence by ZF is significant. Because the reduction of energy flux in D-T with Fast Ions are shown in Fig.6(C) by yellow-bar, I assume the reduction in turbulence intensity should be also observed in CGYRO simulation if the author's claim is correct. So, please show the turbulence intensity by CGYRO calculation in Fig.6. This will be more direct explanations for author's claim."

A comparison of the turbulence intensity between cases is not useful here to analyze the damping effect of the fast-ion-induced zonal flows on the thermal ions. For the same class of turbulence (i.e. same qualitative nonlinear turbulence mode spectrum), reduced turbulence intensity suggests reduced transport. However, turbulence intensity is not the same as transport (it is missing a nontrivial weighing factor) and comparison between different cases when a significant shift in the turbulence spectrum occurs (e.g. from fast-ion-dominated turbulence to ITG-dominated turbulence) is not straightforward. Actually, there is no correlation between turbulence intensity and transport in these cases.

A better measure of the effectiveness of zonal flow damping is to compare the zonal shearing rate between the different cases. Here we use the zonal drift energy (see Eq. (1) in the paper) as a quantitative measure. For the case with fast ions, ω_{ExB}=12.5. For the case without fast ions (where ITG turbulence dominates), the zonal drift energy is significantly reduced ω_{ExB}=0.7. Similar reduction is also observed for the cases where the fast ion instability is artificially suppressed. The significant increase in zonal shearing in the presence of the fast ion instability is consistent with the large reduction in the transport, as suggested in the paper, and therefore we think it is better to leave the paper as it is.