Radiation control in Tritium and Deuterium-Tritium JET baseline plasmas – part II

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In ITER and next step fusion reactors, the chosen materials for the first wall are Beryllium and Tungsten because of their good thermodynamic and mechanical properties, low level of erosion, neutron activation, and Tritium retention. However, radiation events due to the release of such high Z materials, can be responsible of plasma cooling, which can affect the ELM dynamics [A.R. Field et al 2021 Plasma Phys. Control. Fusion 63 095013], trigger MHD instabilities [G. Pucella et al 2021 Nucl. Fusion 61 046020], and inhibit the achievement of thermonuclear temperatures. For these reasons, over the years, methods to control the radiation level have been developed and integrated in the scenario design development.
JET is the ideal testbed experiment where conducting radiation control studies being equipped with an ITER-like wall and able to operate in Tritium and Deuterium-Tritium fuel mixtures in plasmas with input power up to 33 MW. In this work, radiation control in JET ITER-like wall baseline plasmas during Tritium and Deuterium-Tritium baseline operations is reported, complimenting the work presented in [L. Piron et al Radiation Control in Deuterium, Tritium and Deuterium-Tritium JET baseline plasmas – part I]. The behavior of radiation control methods has been investigated statistically. Such an analysis suggests that in Tritium hollow density profiles develop because of the high density level achieved at the plasma edge. This turns out to affect the ELM dynamics, exacerbating the radiation control. A possible solution to counter radiation building up is proposed and consists in exploiting the presence of error field correction coils in JET to mitigate the ELM dynamics, and to induce density pump-out, thus affecting the density profile evolution.

Keywords: JET, Plasma, Real-time control, DT, Tritium Operation, Radiation control, Plasma termination.

1. Introduction

The Joint European Torus (JET) has offered the unique possibility to contribute on radiation control studies in metallic wall conditions similar to ITER, i.e. a Beryllium main chamber wall and a Tungsten divertor, the so-called ITER-like wall, and in plasma scenarios with input power up to 33 MW and reactor relevant fuel mixtures.

With the installation of the JET ITER-like wall, the control of radiation has been challenging because of the tendency of Tungsten and other high-Z impurities, such as Nickel, to accumulate. Such accumulation has been responsible of strong radiation, which can slow down the edge localized mode (ELM) dynamics, inducing H to L transition [1], trigger MHD instabilities [2] and inhibit the achievement of the high temperatures needed for fusion processes, besides imposing a threat on the lifetime of plasma facing components [3].

Especially in the JET baseline scenario at high input power, the radiation is mainly localized in the low field side (LFS) region. Because of the outward neoclassical transport convention [1], impurities tend to be localized in this region from where they can be efficiently flushed by the ELMs. However, if the ELM frequency is too slow and long ELM free periods occur, a runaway radiation event can occur.

It is thus of paramount importance to control in real-time the ELM dynamics to avoid or counter impurity accumulation and monitor the radiation level to take mitigating actions, avoiding a plasma disruption.

The path to radiation control in 3.5 MA plasma current (I_p), 3.25 T toroidal magnetic field (B_t) baseline discharges in Tritium and Deuterium-Tritium, has been described in [4].

In this work, the behavior of the various radiation metrics used to detect radiation building up in these plasmas has been investigated statistically. In particular, Section II describes the radiation metrics available the Real Time Central Controller (RTCC) and in the Plasma Event TRiggering for Alarm (PETRA) system [5], together with their triggering rate. Section III presents the

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statistical analysis of radiation behavior, which suggests that plasma density at the edge can play a major role in determining radiation runaway events. This experimental finding is complemented with TRANSP modelling [6] used to investigate how NBI particle deposition influences the density profile evolution, and thus excessive radiation. Section IV leads the conclusion and a possible solution to cure impurity accumulation in the LFS region is proposed.

2. Behavior of radiation metrics in baseline plasmas

During JET operation, to monitor plasma radiation, a series of metrics have been implemented in programmable schemes in the RTCC system, combining bolometric signals, and deduced by a surrogate model of bolometry tomography based on machine learning [7] in the PETRA system [5].

When a metric is seen to exceed a certain threshold, the JET real-time control system raises a stop, which initiates a controlled termination of the pulse, being not possible to recover a plasma affected by excessive radiation.

Table 1 reports the radiation metrics responsible of a the stop in Deuterium, Tritium and Deuterium-Tritium JET ITER-like wall baseline plasmas, together with the triggering rate. In particular, the metrics responsible of stop in the RTCC system are:

i) Radiation Fraction, defined as the ratio of total radiation power from vertical and horizonal KB5 bolometer channels [8], and the total input power,

ii) Radiation Peaking, defined as the ratio between a central and an off axis vertical bolometer channel,

iii) Horizontal radiation peaking, defined as ratio between the average power in the core bolometer channels to the average power in the edge bolometer channels,

iv) Horizontal radiation over core temperature, defined as ratio between a core bolometer horizontal channel and the central temperature.

On the other hand, the triggered metrics in the PETRA system are the power radiation from the core and power radiation from the edge, which have been estimated using poloidal masks in the core and the LFS regions of the plasma, respectively, over a fast tomography reconstruction and integrating toroidally. In particular, the poloidal mask in the LFS is bounded by a rectangle with coordinates R=(3.382, 3.966) Z=(-0.524,1.313) and covers 69.0% of that rectangle. While, the poloidal mask in the core is bounded by the rectangle with R=(2.484, 3.361) and Z=(-0.177,0.864) and covers 82.1% of that rectangle.

It is worth mentioning that the PETRA system is brand-new. It has been indeed introduced only recently, in 2019. Deuterium plasmas presented here have been performed since 2018, thus not all the Deuterium plasmas have been

	Deuterium	Tritium	Deuterium-Tritium
Metrics	94/220 (43%)	6/8 (75%)	9/17 (53%)
Rad. Fraction	53	5	4
Rad. Peaking	30		
Hor Rad /Te0	2		
Hor Rad Peak			1
Prad core	6		
Prad LFS	3	1	4

Table.1. Statistics of stop due to radiation issues in Deuterium, Tritium and Deuterium-Tritium baseline plasmas. The percentage refers to the number of pulses with radiation events divided by number of pulses performed The metrics implemented in the RTCC system are reported in green, while the metrics implemented in the PETRA system in cyan.

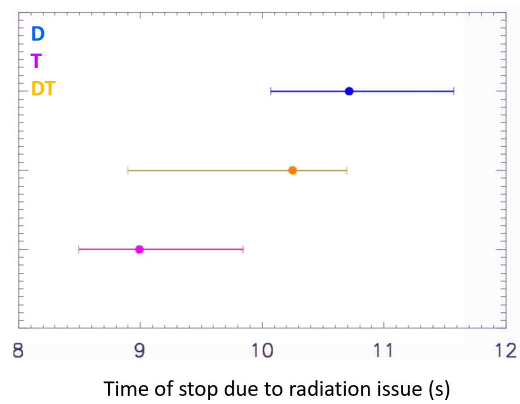

Fig.1. 25th, 50th, 75th percentiles of stop timing distributions of JET baseline plasmas affected by radiation issues and with different fuel mixtures.

monitored by the PETRA system. This justifies why PETRA-based metrics are mostly triggered in Tritium and Deuterium-Tritium campaigns.

Excessive radiation has been the main cause of stop in JET baseline plasma operations using different fuel mixtures, as shown in Table1. The highest rate, 75%, has been achieved in pure Tritium plasmas. The radiation issue developed in fast time scale, 2-2.5 s after the switching on of the NBI injection (at t=7.55 s), as shown by the percentiles of stop timing distribution, shown in Fig.1. Radiation control has been an issue also in more than 50% of DT plasmas and the radiation event occurs slightly later than in T plasmas.

It is worth highlighting that the lesson taken from D operation is that ELM control by means of fuel + pacing pellets is the optimal strategy to avoid radiation building up, while keeping good plasma confinement properties. However, it has been necessary to tune this strategy in Tritium and Deuterium-Tritium plasmas, considering the different ELM dynamics and the slower response of the Tritium injection modules. Efforts have been undertaken to optimize ELM control, as documented in [4], within the limited experimental time and the restrictions on Tritium consumption and neutron activation.

3. Behavior of radiation in JET baseline plasmas

To identify the main conditions which favor radiation runaway events, a statistical analysis of baseline plasmas effected by radiation issues has been carried out.

Data has been collected from 0.5 s after the NBI switching on up to the time of the stop in order to study the evolution of plasma radiation, excluding the effect of mitigating actions against the impending disruption.

The main outcomes of this analysis are reported in Fig.2 and Fig.3. Data refers to baseline plasmas at high plasma current at I_p=3 MA and I_p=3.5 MA and with different fuel mixtures. The quantities reported are the radiation fraction, calculated by the RTCC system, which provides an indication of the total radiation, and the metrics $P_{rad\ LFS}$ and $P_{rad\ core}$, from the PETRA system, which inform where the plasma is radiating. Such quantities are plotted as a function of edge density, at ρ=0.8, as measured by the high resolution Thomson scattering (HRTS) diagnostics in Fig.2, while as a function of the density peakness in Fig.3. The density peakness has been calculated as the ratio between the density from HRTS at ρ=0.15 and at ρ=0.8. This quantity can be intended as a proxy of the density profile. Indeed, when the density peakness indicator is below 1 implies that the density in the core is smaller than the density at the edge, thus a hollow density profile is present.

As anticipated before, the radiated power is mostly emitted from the LFS region as shown by the high level of $P_{rad\ LFS}$ compared to $P_{rad\ core}$, reported in Fig.2(b-c) and Fig2.(e-f), for the I_p=3 MA and the I_p=3.5 MA ensemble, respectively.

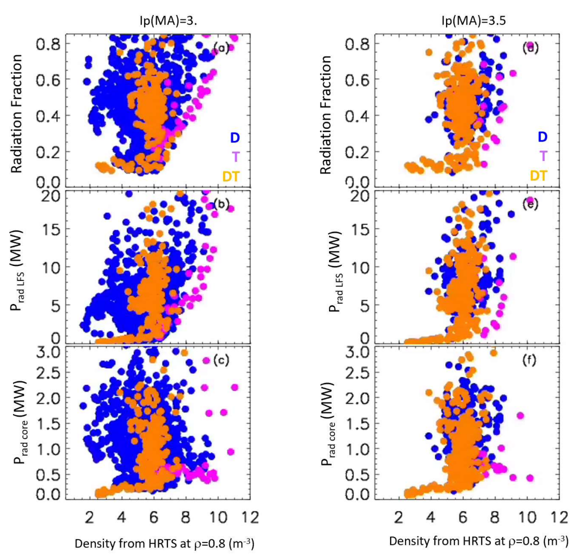

Fig.2. Behavior of (a-d) radiation fraction, (b-e) $P_{rad\ LFS}$ and (c-f) $P_{rad\ core}$ as a function of density at the plasma edge. Data refers to baseline plasmas with different fuel mixtures at 3 MA, on the left, and at I_p=3.5 MA, on the right. The color code has been used to distinguish the different fuel mixtures.

It is also worth noting that in Tritium plasmas, the highest edge density level has been achieved. As it will be described later in this section, this is linked to the NBI particle deposition profile being peaked at the plasma edge. The fact that the density at the plasma edge is higher in T w.r.t to D and DT plasmas implies that particle transport is different and the radiative loss is enhanced, cooling the peripheral plasma and thus affecting the ELM stability. This poses a threat on ELM control.

In particular, when considering the density profile evolution, two paths, with a linear trend, can lead to excessive radiation, either in presence of hollow density profiles, and this is the case when pure Tritium is used as fuel, and in presence of peak density profiles which form in Deuterium-Tritium plasmas, in both 3 MA and I_p=3.5 MA JET baseline scenarios, as shown by the yellow arrows reported in Fig.3(a-d) and in Fig3.(b-e), respectively.

To guarantee T and DT operations without strong radiation, based on the data collected so far, the density peakness indicator should be larger than a min threshold,

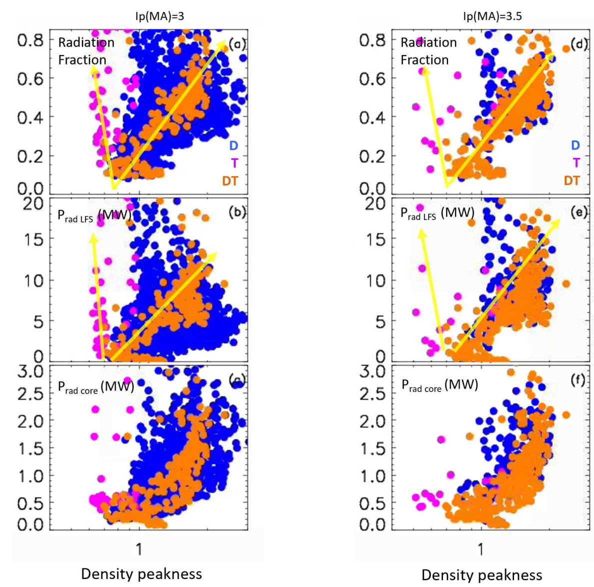

Fig.3. Behavior of (a-d) radiation fraction, (b-e) $P_{rad\ LFS}$ and (c-f) $P_{rad\ core}$ as a function of density peakness indicator, defined in the text. Data refers to baseline plasmas with different fuel mixtures at I_p=3 MA, on the left, and at I_p=3.5 MA, on the right. The color code has been used to distinguish the different fuel mixtures.

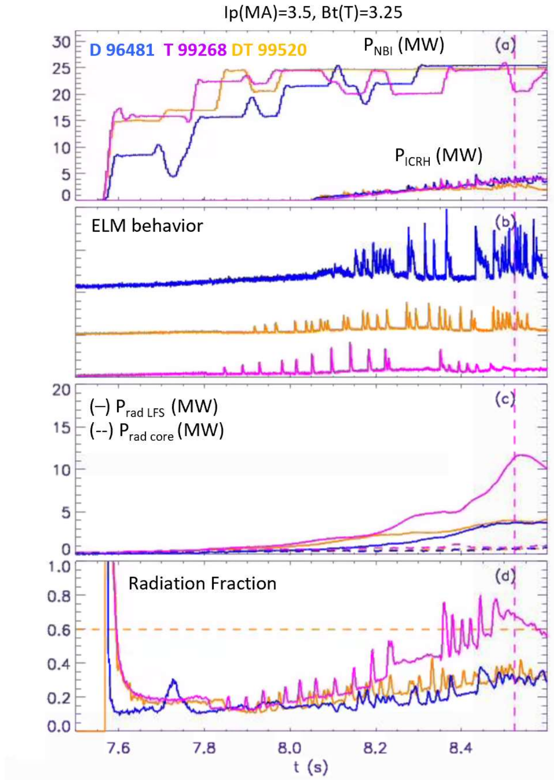

Fig.4. Time behavior of (a) auxiliary heating power, (b) ELMs, (c) radiation in the core (dotted line) and in the LFS (solid line) as calculated by bolometer tomography based on machine learning and (d) radiation fraction in three of I_p=3.5 MA, B_t=3.25 Deuterium, Tritium and Deuterium-Tritium discharges. The time of stop in the Tritium plasma is highlighted with a dotted line.

around 0.8, and be lower than a max threshold, around 1.7. As describing in the following, a proper control scheme based on density peakness can be designed in preparation to DTE3 campaign to avoid such radiation events.

To investigate why Tritium plasmas develop hollow density profiles and thus are more prone to radiation runaway events, the TRANSP modelling [6] has been applied. Here, an example of this study is provided considering the set of discharges reported in Fig.4. These discharges have been performed at I_p=3.5 MA plasma currents and with high auxiliary power, and differ from the fuel mixture. The discharge which develops in relatively fast scale (1 s after the NBI injection) high radiation content is the Tritium one. As shown in Fig4. (c), the radiation is localized in the LFS region. Despite the presence of some ELMs, which have been paced at 25 Hz by pellet injection, as described in [4], an ELM free phase occurs which causes heavy impurity accumulation, leading inevitably to radiation increase. The radiation increases to more than 60% of the input power, as shown in Fig.4 (d), at which point this triggers a controlled termination of the pulse.

As described in [4] and shown in Fig.5(a), the plasma density in these discharges has been adjusted to be at the same level at the H mode. However, the edge density especially in the Tritium plasma grows in time, causing hollowing of the density profile.

The density at the edge increases in this way because, despite the same NBI beam energy injected, shown in Fig.5 (e), when using Tritium, the injected particle velocity is lower w.r.t. the one in Deuterium and Deuterium-Tritium. Hence the beam penetration is correspondingly lower, and mainly localized in the LFS, as foreseen by TRANS modelling of beam particle deposition profiles reported in Fig.5 (f).

How the hollow density profile, the ELM behavior and the radiation building up are linked each other within a chain of causality is a complex matter of study, which involves ELM stability, PLH threshold, the power threshold for the low to high confinement transition, and transport considering isotope effects. Dedicated analyses are ongoing and the main outcomes will be reported in a separate paper.

This statistical analysis presented here highlights that hollow density profiles due to the high density achieved at the plasma edge lead to radiation building up. Ad-hoc metrics, based on density peakness indicator can be implemented in real-time using HRTS or interferometer signals to monitor the density profile evolution, similarly to the temperature hollowness indicator described in [9].

Proper actions can be envisaged to counter the development of hollowing of density profiles. First of all, a proper particle flushing shall be guaranteed by an efficient ELM dynamics which envisages an optimization of the settings in the gas valves and pellet injector, the actuators of ELM control. Besides this control strategy, also 3D magnetic fields induced by error field correction coils can prevent the radiation building up through a

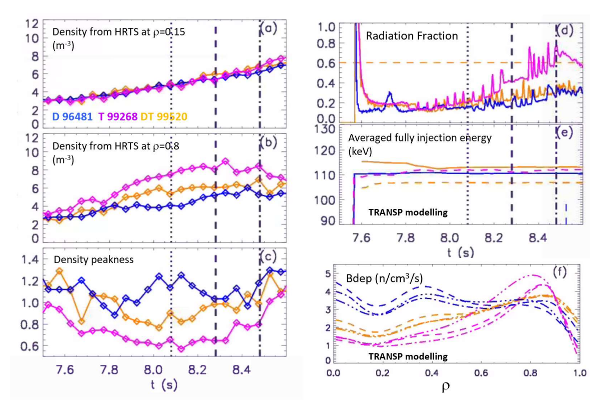

Fig.5. Time behavior of (a) core and (b) edge density, (c) density peakness indicator, (d) radiation fraction and (e) averaged fully injection energy from TRANSP modelling. Profile of NBI beam particle deposition from TRANSP modelling at various time instants, indicated in the figure with different line styles. The color code has been used to distinguish the various fuels used in

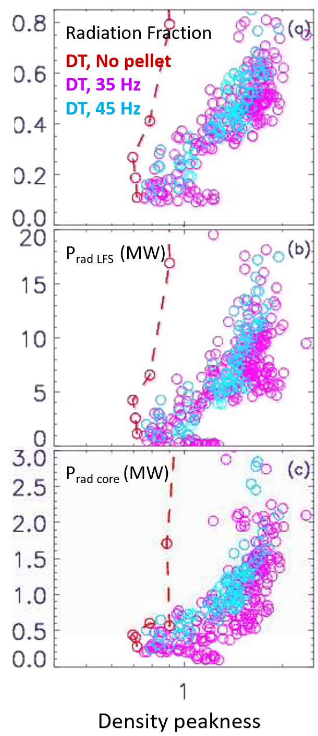

Fig.6. Behavior of (a) radiation fraction, (b) $P_{rad\ LFS}$ and (c) $P_{rad\ core}$ as a function of density peakness indicator of DT baseline plasmas with I_p=3.5 MA plasma current. The color code has been used to distinguish the different pellet injection frequency.

double effect. 3D magnetic fields can increase the ELM frequency, as documented in [10], favoring the expulsion of heavy impurities, and induce density pump-out, so can affect the density profile evolution, and thus plasma transport. When applying 3D magnetic field, a breaking of rotation through the neoclassical viscosity torque is foreseen, which impacts plasma transport, as well. To assess how these mechanisms influence radiation building up, proper experiments should be carried out. We propose to apply 3D magnetic fields at low plasma current, at around 2 MA, to study the impact of such perturbations on the ELM dynamics and the density profile evolution and based on the results achieved, investigate the portability of this method at higher plasma currents.

It is worth noting that a hollow density profile which leads to a radiation runaway event, can occur also in DT plasmas. This turns out to be the case when the pellet injector, because of the mechanical problem, didn't launch pellets and so an efficient pacing ELM flushing hasn't be granted.

This is demonstrated in Fig.6 which shows the behavior of radiation fraction and the power from the LFS and the core as a function of the density peakness in I_p=3.5 MA DT baseline plasmas. The color code has been used to distinguish the various pellet inject frequencies. Note that in case of missing pellets, the plasma exhibits hollow density profiles, which leads to a significant increase of radiation, localized in the LFS, as shown in Fig.6(b). This enforces the proposal of developing a density hollowness indicator, which can be used in DTE3 in case of pellet injection failure, allowing the save Tritium.

The statistical analysis carried out shows also that the change of the pellet injection frequency, from 35 Hz to 45 Hz didn't not affect radiation control in DT plasmas. Indeed, the radiation metrics reported in Fig.6 follow the same trend as a function of the density peakness.

4. Conclusion

In this work, radiation control in D, T and DT JET ITER-like wall plasmas has been presented considering the statistics of the stop triggering and analyzing radiation metrics as a function of the density behavior.

After the T and DTE2 campaigns, it is possible to conclude that, especially in T, keeping the radiation under control is more difficult. This is associated with the different dynamics of ELMs which have a slower frequency, a smaller amplitude and a compounded nature w.r.t. Deuterium and Deuterium-Tritium plasmas. At present, the edge density regimes achieved in JET operating in Tritium seem to play a role on the different ELM dynamics observed. Detail studies are ongoing, including PLH threshold and plasma transport, to further investigate this point.

Data collected so far suggests that in T and DT there are two paths, identified by the evolution of density profiles, which can lead to radiation building up, either hollow density profiles and too peaked density profiles. The hollowing of density profiles is not only a feature of Tritium plasmas, but can occur also in a DT plasma in case of failure in the pellet injector. This highlights the importance of a reliable pellet injector in ITER or in next step fusion reactors to control the high Z impurity accumulation by promoting frequent ELMs.

To monitor the radiation evolution, new metrics based on the density peakness have been proposed and remedial actions based on the exploitation of EFCCs has been suggested. Indeed, EFCCs can mitigate the ELM dynamics and induce density pump out, thus affecting the density profile and plasma transport. To assess the effectiveness of using the EFCCs to avoid radiation accumulation, proper tests need to be performed in preparation to DTE3.

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