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**ABSTRACT**

We define a parameter $\beta_r$ for all plasmas that can be used to detect the pollution of the plasma bulk by highly radiative impurities. This parameter is defined as the radiative loss of the mixture of impurities relative to their mean $Z^2$. We show that this parameter, though global, is very sensitive to the presence of highly radiative impurities in the bulk of the discharge. We use it to compare JET plasmas in the carbon environment and in the ITER-like wall (ILW), where it is highly correlated to the level of a bundle of spectroscopic lines of tungsten passing through the centre of the discharge. In the carbon environment, the value of $\beta_r$ is around 1, indicating the absence of highly radiative impurities in the plasma. No change or even a small decrease is observed when going from L-mode to H-mode, this robustness being in agreement with the multi-machine scaling [1]. In the ILW machine, the value of $\beta_r$ is found to depend on the type of additional heating and confinement state of the plasma. We observe that neutral-beam injection (NBI) introduces little W into the plasma, with a $\beta_r$ between 2 and 3. Ion-cyclotron radio-frequency (ICRF) waves yield a $\beta_r$ of order 5 in L-mode and 10 in H-mode when no edge-localized modes (ELMs) are present. Conversely when ELMs are present, the parameter goes back to 5, illustrating the positive effect they can have on the bulk pollution by tungsten.

## 1. INTRODUCTION

Currently tungsten is being investigated as the preferred future material for tokamak divertors as its use solves several problems:

Firstly fuel retention should be minimized by the use of tungsten [2,3]. Another positive aspect is that tungsten is eroded at higher plasma temperatures than carbon [4]. At the moment it is being tested in a number of tokamaks [5] and is envisaged as the primary material for the divertor of ITER. However, apart from these qualities, there are some difficulties to operate machines with this type of high-$Z$ material, in particular because it can radiate in the plasma core [6,7]. The presence of radiation in the centre of the discharge is a major concern for fusion machines and efforts are being made in present experiments to identify the radiating impurities in the core and estimate their concentration [8,9].

Spectrometers used for this purpose cover only lines or bundles of lines of these high-$Z$ impurities along a few lines-of-sight and it is difficult from these measurements to deduce their concentrations. This can be done, in principle, with the help of radiation models which calculate the ionization equilibrium and which must include also the transport of the impurities. For high-$Z$ elements, however, even the best of these models are only approximate. The case of tungsten is particularly difficult since many coefficients of radiative transitions in the highest ionization states are presently unknown.

As a result any information that can be gained about the radiative efficiency of the impurities polluting the bulk can be useful. This paper is a step in that direction. We analyze data from JET in its ITER-like wall (ILW) configuration [10] with tungsten divertor and beryllium torus walls and compare it with similar data from the earlier carbon environment.

We show that even global parameters can carry useful information about the type of impurities polluting the bulk of the discharge. In order to do this, we establish the relationship between the bulk radiated power, the effective charge $Z_{\text{eff}}$ of the discharge and the line-averaged density $n_e$. We deduce from this relationship a parameter $\beta_r$ that turns out to be the radiative loss parameter of the mixture of impurities relative to the square of their mean charge.

The value and the changes of this parameter indicate a change of the impurity mixture and the pollution of the plasma by highly radiative species becomes immediately visible regardless of the amount of radiated power.

In section 2 we introduce the relationship between $P_{\text{radbulk}}$, $Z_{\text{eff}}$ and $n_e$ that allows calculation of $\beta_r$ and gives its units. In section 3, the physical meaning of $\beta_r$ is discussed in the light of the "radiative loss parameter" of the impurities as defined in reference [11]. In section 4, we discuss the filtering and influence of ELMs on determination of this parameter. Section 5 is dedicated to carbon-environment plasmas where we observe the changes in the $\beta_r$ parameter from L- to H- mode. In section 6 we discuss the link and the differences of our approach with the multi-machine scaling. Section 7 is dedicated to the results obtained in the ILW environment. In 7.a we monitor first the different effects of NBI and ICRF waves on $\beta_r$ in L-mode plasmas. In 7.b and 7.c we observe the L-H transition both for pure NBI and ICRF plasmas. In 7.d, we observe the correlation of $\beta_r$ with the spectroscopic lines of high-$Z$ impurities and discuss the effect of tungsten events on the evolution of the parameter. We finish in section 8 with the conclusions.

## 2. GENERAL DEPENDENCE OF $P_{\text{RAD}}$ WITH $Z_{\text{EFF}}$ IN THE PLASMA BULK.

The radiative power in the plasma bulk due to impurities can always be written in the following way:

$$P_{\text{radbulk}} = \beta_r \, (Z_{\text{eff}} - 1) \, n_e^2 \tag{1}$$

where $n_e$ is the line-averaged density provided by high-resolution Thomson scattering [12] and $Z_{\text{eff}}$ is calculated from bremsstrahlung emission [13] measured along a horizontal line-of-sight crossing the plasma centre (i.e. not passing through the divertor region). $P_{\text{rad}}$ in the bulk is evaluated by bolometry, on JET using its most recent cameras (KB5) [14]. In order to estimate the bulk radiated power, bolometric horizontal lines-of-sight in the top half of the plasma only are used. The volume covered by them is then stretched to fill the whole plasma volume. In JET, we neglect the bremsstrahlung and cyclotron radiation; however, in a machine such as ITER, this will not be possible anymore and these quantities will have to be calculated or measured and removed from the total radiated power before evaluating $\beta_r$.

We give the expression for $\beta_r$ in a general case where different types of impurities with different ionization levels are present in a deuterium plasma.

Firstly, for only one type of impurity, the radiated power (W) in the bulk may be written as:

$$P_{\text{radbulk}} = n_e \, n_{\text{imp}} \, V \sum_i a_i \, b_i \, c_i \, L_{ti}.$$

In this expression $n_{\text{imp}}$ is the total impurity density, $n_e$ the electron density, $a_i=n_i/n_{\text{imp}}$ the fraction of impurity ions with charge $Z_i$, $b_i=n_{ei}/n_e$, the fraction of the density in the volume where the ion with charge $Z_i$ radiates and $c_i=V_i/V$ the fraction of the volume in which the same ion radiates. $L_{ti}$ is the radiative cooling function for the same ion with charge $Z_i$. We suppose in this expression that the electron temperature $T_e$ is homogenous in the volume where the ion of charge $Z_i$ is radiating, as well as the density of impurity ions and electrons. This is only an approximation. If we extend this to multiple impurities we get:

$$P_{\text{radbulk}} = n_e \, V \sum_k n_{\text{imp}}^k \sum_i a_i^k \, b_i^k \, c_i^k \, L_{ti}^k,$$

where $k$ denotes different types of impurities. We can write the expression for $Z_{\text{eff}}$ as:

$$Z_{\text{eff}} = 1 + \frac{1}{n_e} \sum_k n_{\text{imp}}^k \sum_i a_i^k \, Z_i^k \, (Z_i^k - 1).$$

If we combine these expressions in relation (1), we find

$$\frac{\beta_r}{V} = \frac{\sum_k \varepsilon_{\text{imp}}^k \sum_i a_i^k b_i^k c_i^k \, L_{ti}^k}{\sum_k \varepsilon_{\text{imp}}^k \sum_i a_i^k \, Z_i^k (Z_i^k - 1)} \quad (2) \quad \text{where} \quad \varepsilon_{\text{imp}}^k = \frac{n_{\text{imp}}^k}{\sum_k n_{\text{imp}}^k}.$$

We notice that $\beta_r/V$ is not dimensionless; it has the dimension of $L_t$ and can be expressed in $\text{W.m}^3$.


### 3. THE PHYSICAL MEANING OF $\beta_r$

The radiative loss parameter of an impurity $k$ is defined in reference [11] as $S_k = \hat{P}_{\text{rad}k} / (n_e \, n_k)$, where $\hat{P}_{\text{rad}}$ is radiated power density ($\text{W/m}^3$). It can be calculated using the same notations used in section 2.

We find in this case that for an impurity k, $S_k \approx \sum_i a_i^k \, b_i^k \, c_i^k \, L_{ti}$ where $i$ takes account of the different ionization states.

Hence $\beta_r$ can be expressed as a function of the radiative loss parameter of the impurities as:

$$\frac{\beta_r}{V} \approx \frac{\sum_k \varepsilon_{\text{imp}}^k \, S_k}{\sum_k \varepsilon_{\text{imp}}^k \sum_i a_i^k \, Z_i^k (Z_i^k - 1)}. \tag{3}$$

$\beta_r$ is the weighted sum of the radiative loss parameters of the different impurities divided by the weighted sum of their average $Z^2$. In reference [11], $S_k$ has been calculated for different types of impurities in the bulk of the ASDEX Upgrade plasma using a coronal model. The coronal approximation can be used if the residence time of the impurities in the plasma is sufficiently long, which turns out to be the case in the plasma bulk (in contrast to the SOL and divertor region). The result does not depend strongly on the plasma density as long as multi-step processes are weak. If we take the two main impurities for the JET shots (carbon for the carbon divertor and tungsten for the ILW configuration), the results shown in figure 1b of reference [11] show that the $S_W$ for

tungsten has a value of order $10^{-31}$ Wm$^3$ while it is less than $10^{-34}$ Wm$^3$ for carbon. For W, the radiative loss parameter increases moderately for $T_e$ above 100eV (about a factor of 2 between 100eV and 3keV), while it decreases by a factor of 10 for carbon in the same range. Tungsten is at least 3 orders of magnitude more efficient at radiating in the bulk than carbon. This is the well-known result that a tiny fraction of tungsten ($\sim 10^{-4}$) can drive a large radiation loss in the bulk.

The changes of $\beta_r$ may be discussed in the light of these results. In the case of W pollution, the rather weak dependence of $S_W$ with $T_e$ leads to the conclusion that an increase of $\beta_r$ must be associated with an increase of the relative concentration of W in the bulk $\varepsilon^w_{imp}$ (even if this increase is not sufficient to have a measurable impact on $Z_{eff}$). The second point is that the value of $\beta_r$ is liable to be very resilient to $T_e$ changes. A decrease of $\beta_r$ can have different causes. It can be triggered by an increase of low $Z$ impurities that have a very small radiative loss parameter (increase of $Z_{eff}$ and of the denominator in relation (2)), or a decrease of the fraction of tungsten impurities $\varepsilon^w_{imp}$ (no or small change in $Z_{eff}$), or a combination of these two processes, as is occurring during impurity seeding, for example. Finally, therefore, in the ILW changes in the values of $\beta_r$ will always indicate a change in the bulk impurity mixture.

## 4. EXPERIMENTAL DETERMINATION OF $\beta_R$, FILTERING

$\beta_r$ can be simply calculated as:

$$\beta_r(t) = \frac{P_{radbulk}(t)}{(Z_{eff}(t)-1)\, n_e^2(t)} .$$

The value of $\beta_r$ is interesting to follow during a plasma shot to check rapidly if the mixture of impurities contaminating the bulk evolves. However strong events such as ELMs [15] may affect relation (1) or even break it, so that it is in principle necessary to filter the data to remove these non-stationary phases before computing $\beta_r$. However we show that from an operational point of view, $\beta_r$ can be calculated without filtering. There are two reasons for this: $P_{rad\, bulk}$ is quite insensitive to ELMs that are edge phenomena, and $Z_{eff}$ and $n_e$ are line-averaged quantities rather resilient to edge changes. In order to illustrate this, we show in Figure 1 $\beta_r(t)$ calculated for a 12 MW NBI H-mode shot with very large Type I ELMS where first a histogram filtering is applied on the ELMs (Fig.1, left) and second without ELM filtering (Fig.1, right). This comparison shows that even without filtering, the value of $\beta_r$ can be reliably recovered and followed in time.

## 5. CARBON ENVIRONMENT L- AND H-MODE.

The results which we present are selected from the whole JET database and several thousand shots have been scanned automatically. Although only the results from a few shots are presented here, they do represent very well the behaviour of the whole data base. In Figure 2 $\beta_r$ is plotted for an L-mode shot with low NBI power (1.4MW). It is found to be very close to 1 throughout the heating phase. In Figure 3, the same parameter is plotted for an H-mode shot with ELMs. Two heating phases are present, the first with 9MW of NBI power, the second with 19MW of NBI power. Figure

3 shows that that the 9MW phase has a value of $\beta_r$ close to 1 as in L-mode. At 19MW, $\beta_r$ decreases to 0.5. This decrease may be attributed to the behaviour of the radiative loss parameter of the light impurities and carbon ($S_C$) in particular. As the additional heating power is increased, $T_e$ increases in the whole bulk including the pedestal region. As a consequence, the radiative loss parameter of carbon decreases (numerator of relation (2)) even if the denominator stays constant ($Z^2$ of the impurities), thus yielding lower $\beta_r$ values. This simply indicates that the low-$Z$ impurities become even less efficient at radiating in the bulk when $T_e$ is increased. We notice that at NBI heating power below 10 MW, the $\beta_r$ value is the same in L- or H-mode. This shows how robust the value of the $\beta_r$ parameter is in carbon discharges, an observation which partly explains the robustness of the multi-machine scaling [1].

## 6. SIMILARITIES AND DIFFERENCES WITH THE MULTI-MACHINE SCALING.

The multi-machine scaling of plasma purity with radiated power [1] was derived at a time when most of the tokomaks involved were equipped with carbon wall components. The most common impurity in the plasma apart from carbon was oxygen, which is another low-$Z$ impurity also radiating at low $T_e$. The scaling was used to characterize the total radiated power (bulk and divertor) in a situation where it was dominated by the radiation of low-$Z$ impurities. Such a situation implied that most of the time, the radiated power in the divertor was larger than that from the bulk. The simplified form of the multi-machine scaling reads as:

$$Z_{\text{eff}} \approx 1 - 7.5 \frac{P_{\text{rad}}^{\text{tot}}}{A \, n_e^2} \tag{4}$$

where $P_{\text{rad}}^{\text{tot}}$ is the total radiated power and $A$ the plasma envelope area.

The functional dependence that we use for the determination of $\beta_r$ is the same as for the multi-machine formula but with just a few differences. Firstly, $\beta_r$ is only defined for the radiation of the bulk plasma, $P_{\text{radbulk}}$, while the multi-machine scaling deals with the total radiated power. Secondly, $\beta_r$ has a meaning for all plasmas because it is defined in a general way. Thirdly, we do not consider $\beta_r$ as a statistical parameter inferred from a fit but as a dynamical one whose evolution during a discharge can be monitored to detect the impurity changes in the bulk. It can take different values for different types of plasma and plasma phases when the multi-machine scaling proposes a constant parameter only globally dependent.

We apply the multi-machine scaling to the data of the shot displayed in Figure 3. The result (Figure 4) shows moderately good agreement with the scaling with some dispersion.

In general, we find that for experimental values of $\beta_r < 4$, there is reasonable agreement of the data with the multi-machine scaling. For $\beta_r > 4$ the multi-machine scaling departs increasingly from the data for rising $\beta_r$. This result shows that the multi-machine scaling only applies when the bulk radiated power is dominated by the radiation of light impurities. The multi-machine scaling corresponds to the lowest radiation state of the bulk plasma and does not apply when high-$Z$ impurities start to dominate the radiation in that region.

## 7. ITER-LIKE-WALL ENVIRONMENT
### 7.1 SPECIFIC EFFECTS OF ICRF AND NBI HEATING IN L-MODE

In the carbon environment, its surfaces are eroded by physical and chemical erosion but there are also specific interactions of the additional heating with the walls. In the ILW environment, these specific interactions with the wall and divertor structure are critical and the level of tungsten sent to the bulk of the discharge may depend on the type of additional heating. This is examined by comparing ICRF and NBI heating at same power during stationary L-mode conditions. The scenario of the shot plotted in Figure 5 shows that during ICRF heating $Z_{eff}$ is larger than during NBI heating. This suggests that during ICRF more low-$Z$ impurities are also released (such as Be) than during NBI heating, suggesting stronger interaction with the walls. However, the value of $\beta_r$ is 7 during ICRF and 3 during NBI heating. This clearly shows that during ICRF the bulk plasma is more polluted by highly radiative impurities than during NBI operation.

If we compare these results with those obtained in the carbon environment, we see that during NBI heating in the ILW, the lowest value of $\beta_r$ is somewhere between 2 and 3, while the average value in carbon is 1. This higher value suggests that even with NBI heating some small amount of tungsten is nevertheless added to the bulk.

### 7.2 ILW TRANSITION FROM L- TO H-MODE WITH NBI ONLY.

Figure 6 illustrates behaviour when there is an L-H transition with NBI heating. We notice first that the value of $\beta_r$ during the L-mode phase (8s<$t$<10s) is lower than that measured in L-mode in the shot above (Pulse No: 81855), 2.2 instead of 3. The pollution of the plasma by high-$Z$ impurities depends on its history and using NBI after ICRF is less favourable than operating with NBI heating only. We have measured values as low as 1.3 for some ILW plasmas during NBI heating, close to those measured in carbon pulses. During the H-mode phase (10s<$t$<14s), $\beta_r$ increases from 2.2 to an average 3.7, a 68% increase, though the additional heating power is increased from 1.5MW to 10MW. This result illustrates the fact that in this scenario, NBI heating does not produce a large amount of high-$Z$ impurities whether in L- or H-mode. The fact that $Z_{eff}$ remains unchanged also indicates that the pollution by low-$Z$ impurities does not increase either.

### 7.3 ILW TRANSITION FROM L- TO H-MODE WITH ICRF ONLY

In Figure 7, a plasma where only ICRF is used triggers an H-mode transition. This is visible in the plasma traces where the D_alpha signal drops at $t$=17.27s. The energy stored in the discharge is not sufficient to trigger ELMs. This type of shot has been studied and reported in [16]. After the transition, $\beta_r$ increases from 5 to 10, a 100% increase. $\beta_r$ around 10 is the level commonly observed in the JET database when ICRF triggers H-modes without ELMs. It is one of the highest values obtained so far for $\beta_r$. As the level of $\beta_r$ jumps to 10 immediately after the ICRF power has reached the threshold, it can be speculated that this is partly the effect of the transport change. As transport decreases in the bulk after the H transition, the amount of impurities there increases. There are other indications of fluctuation effects on $\beta_r$ when ICRF power is being used. For example, when ELMs

are present in the discharge, a combination of NBI and ICRF heating power produces $\beta_r$ values of order only 5. Once the NBI is decreased and the ELMs disappear, $\beta_r$ reverts to 10. This illustrates the beneficial effect of ELMs for ejection of impurities from the bulk.

## 7.4 LINKAGE OF $\beta_R$ WITH IMPURITY LINES MEASURED IN THE DISCHARGE.

$\beta_r$ is the radiative loss parameter of the mixture of impurities polluting the bulk relative to its mean $Z^2$. As the radiative loss functions of the impurities scale roughly as the cube of their charge [11], the $\beta_r$ values are extremely sensitive to the amount of highly radiative impurities such as tungsten in the discharge; thus $\beta_r$ is a potent parameter to detect them. As a result it can be expected that $\beta_r$ should be correlated with the spectroscopic lines of these highly radiative impurities. This is indeed the case, as is shown in Figure 8. $\beta_r$ is plotted as a function of time together with a bundle of tungsten lines emitted from the centre and a line of nickel XVIII radiated at the edge of the bulk plasma. To facilitate comparison of the different signals, they are normalized to the same scale. The data in Figure 8 show that $\beta_r$ is extremely well correlated with the bundle of W lines and not at all with the nickel one. As a result, the increase of the bulk radiation at the beginning of the NBI heating phase can be unambiguously attributed to emission by tungsten. Another point is that $\beta_r$ can detect a pollution of the bulk plasma after a so-called tungsten event, i.e. a sudden large influx typically due to ingression of a dust grain or flake [17]. This is illustrated in Figure 9 which shows the variation of $\beta_r$ during a time window where such an event occurs in a 9.4 MW NBI heated H-mode shot. The ELMs have not been filtered and are visible on the data. It is unclear at the moment the exact role they play in the recovery time of the radiation profile which exactly matches the recovery time of the $\beta_r$ parameter. We note however a drop of the βr parameter at 13.5s that corresponds to the crash of a very large ELM. Before the tungsten event, at 13.4s, $\beta_r$ has a value of 2.6, then after the event at 13.7s, it goes back to a value around 4, indicating that some tungsten has been added to the bulk of the discharge and is radiating there. This is confirmed by the bolometry data which show peaking of the radiation in the mid-plane on the low-field side of the plasma (the usual signature of tungsten radiation with NBI heating [18]) after the tungsten event. Notice also that before the tungsten event, the value of $\beta_r$ was quite low and in agreement with that usually observed with NBI heating.

## CONCLUSIONS

We have shown that a global time-dependent parameter can give fast and reliable information about the presence of highly radiative impurities in tokamak discharges. It can be calculated for all plasmas regardless of the scenario and of the confinement state. We have compared JET shots in the carbon environment with ones in the ILW. The very low values obtained in the carbon environment clearly indicate the absence of significant radiation from highly radiative impurities in the bulk plasma, with an average value of $\beta_r \approx 1$. One of the striking results in carbon is that the variation of $\beta_r$ with the plasma scenarios is small. This result partly explains the robustness of the multi-machine scaling [1] that applies to carbon-dominated plasmas and proposes a constant coefficient of the

scaling for each machine. When switching to the ILW environment, we observe that $\beta_r$ increases above 1, this increase being clearly dependent on the plasma scenario: viz. the confinement mode, the fuelling of the plasma, and the type of additional heating used. By comparing the effect of the different types of additional heating, we observe that plasmas heated with NBI have relatively low $\beta_r$ values of order 2 to 3 times those measured in the carbon environment. This indicates that NBI heating sends little tungsten into the bulk. During the L-H transition the $\beta_r$ parameter is observed to increase moderately even with a sevenfold increase of the NBI power. This situation compares well with the carbon environment and confirms low pollution by tungsten. We notice however that even with this type of additional heating, tungsten emission events do occur and can lead (in the case of strong events) to pollution of the core by additional tungsten. $\beta_r$ is strongly correlated to the bundle of W lines measured in the centre of the discharge but can still detect W pollution even when the radiation is displaced out of the spectroscopic lines-of-sight. In the case of ICRF heating, these plasmas systematically yield $\beta_r$ values of order 5 in L-mode and 10 in H-mode if no ELMs are present. In the presence of ELMs, $\beta_r$ values are reduced back to a value of 5, illustrating very well the beneficial effect of ELMs on W pollution. In the ILW, we have not observed so far (experimental campaigns 2011, 2012, 2013) values of $\beta_r$ below 4 when ICRF power is being used to heat the plasma. These values are extremely robust over the entire database and clearly indicate that ICRF introduces more tungsten in the discharge than NBI heating.

Finally $\beta_r$ is a global parameter that is not straightforward but it has some advantages: it is extremely sensitive to the pollution of the plasma by highly radiative impurities and can detect them when no other diagnostic is available. It has also the virtue of being easily calculated with standard measurements and can be determined even without ELM filtering. Its time evolution can be followed during a shot and provides quantitative values which can be compared from shot to shot. For these reasons, it could be useful for many machines, including ITER.

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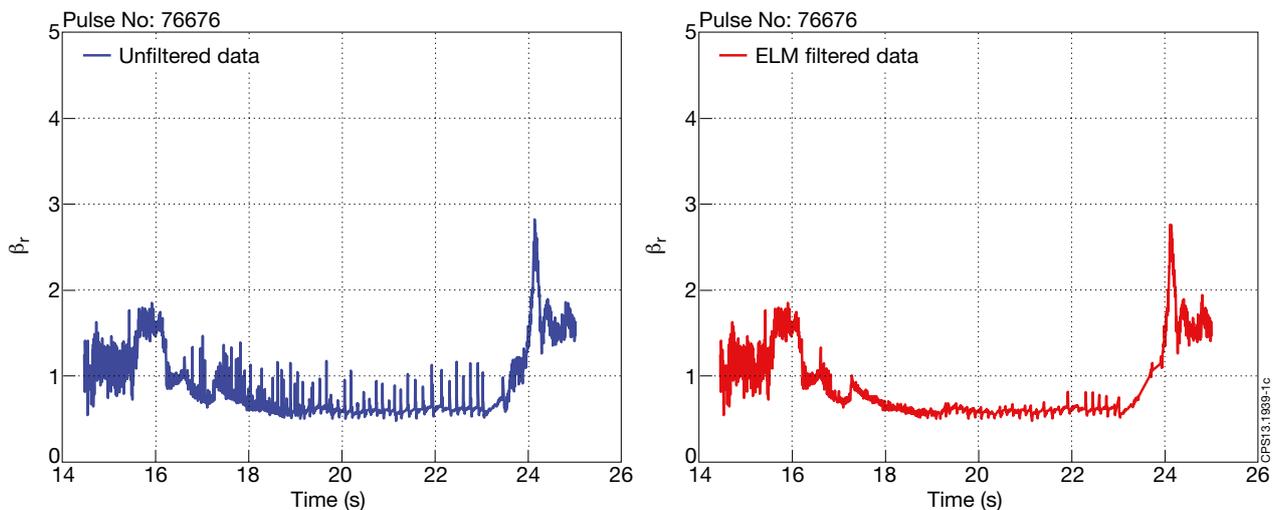
*Figure 1: Pulse No: 76676, carbon environment. H-mode, 12MW NBI heating. The result displayed is for the NBI heating phase only. Left) $\beta_r$ determined with ELM-filtered data. Right) $\beta_r$ determined with unfiltered data.*
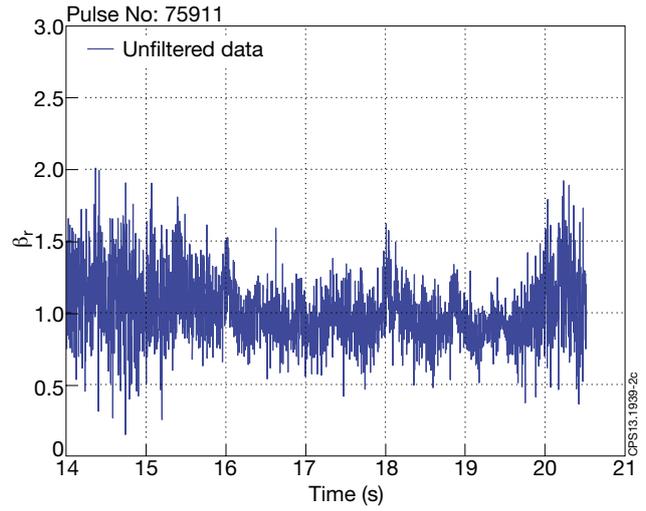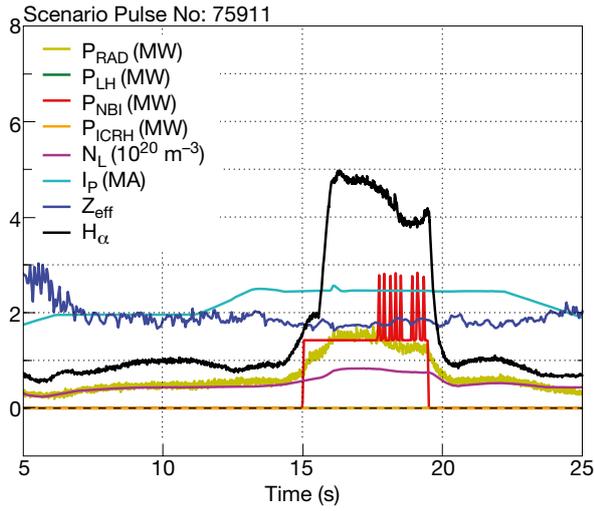
*Figure 2: Left : scenario for Pulse No: 75911, L-mode, NBI from 1.4 to 2.8MW Right: $\beta_r$ calculated during the NBI heating phase.*
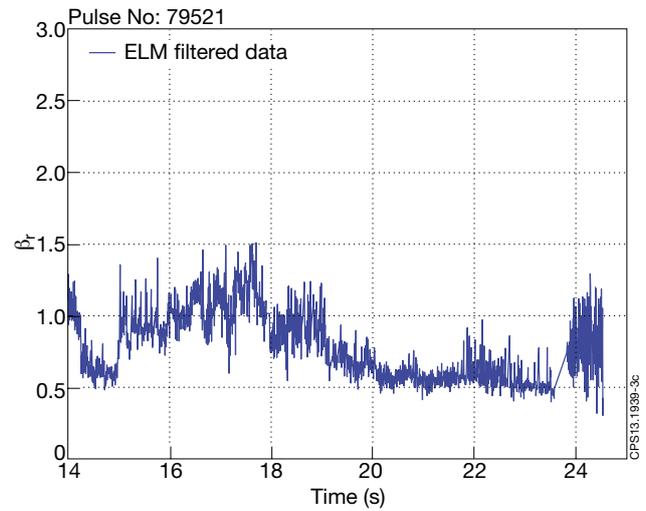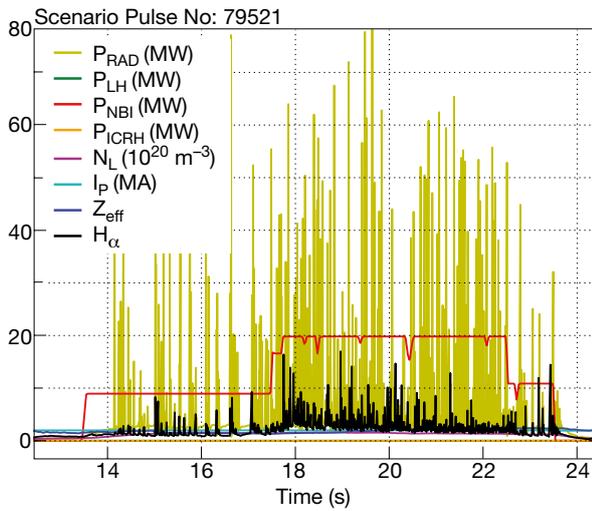


*Figure 3: Left) scenario of Pulse No: 79521, carbon mode. Right) $\beta_r$ calculated during the NBI additional heating phase.*
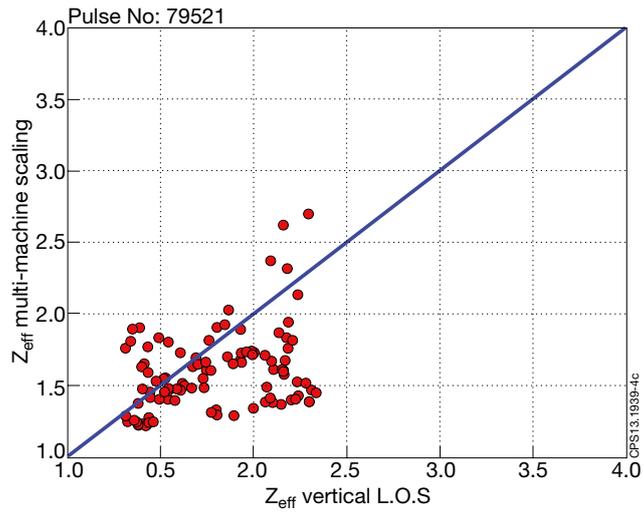
*Figure 4: Test of the multi-machine scaling using relation (4), Pulse No: 79521, carbon environment, H-mode, NBI heating phase.*
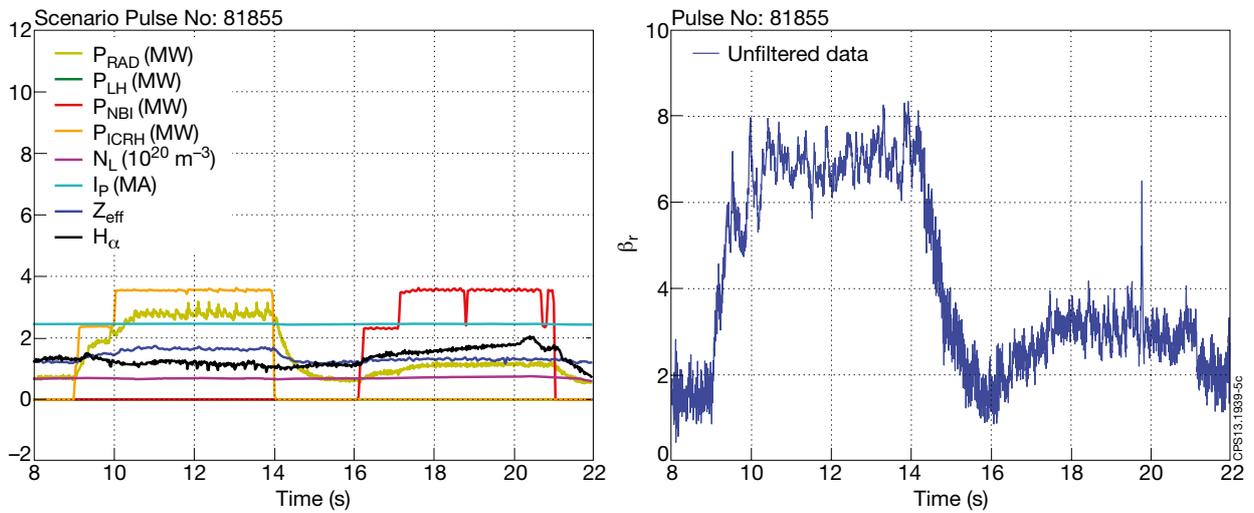


*Figure 5: Left) scenario of Pulse No: 81855, L-mode, ICRF then NBI heating. Right) value of $\beta_r$ calculated during the additional heating phases.*
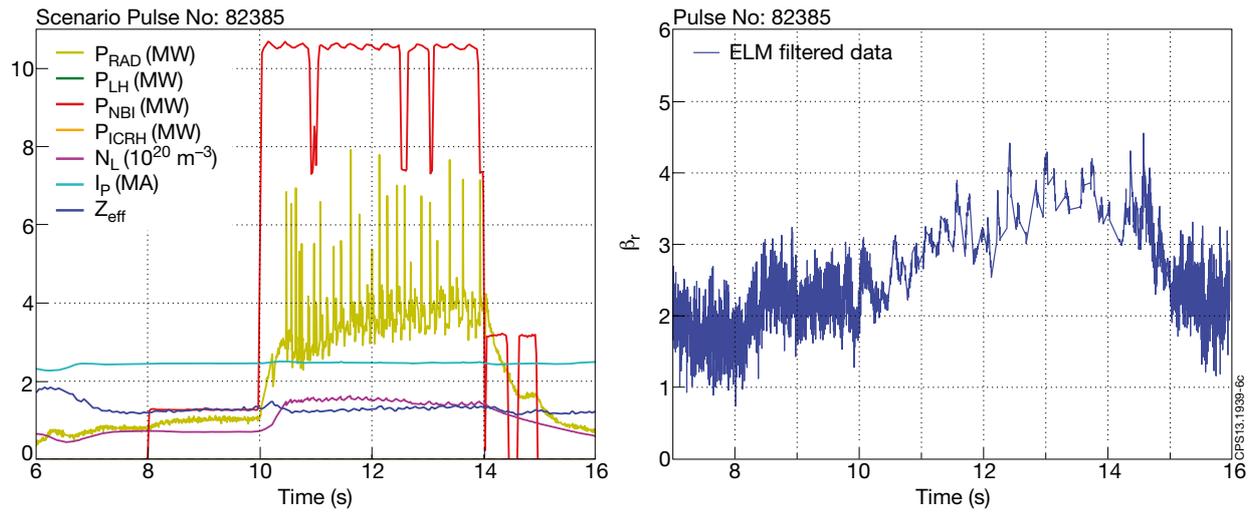
*Figure 6: Left) scenario of Pulse No: 82835, L-H transition, NBI heating. Right) value of $\beta_r$ calculated during the additional heating phases.*
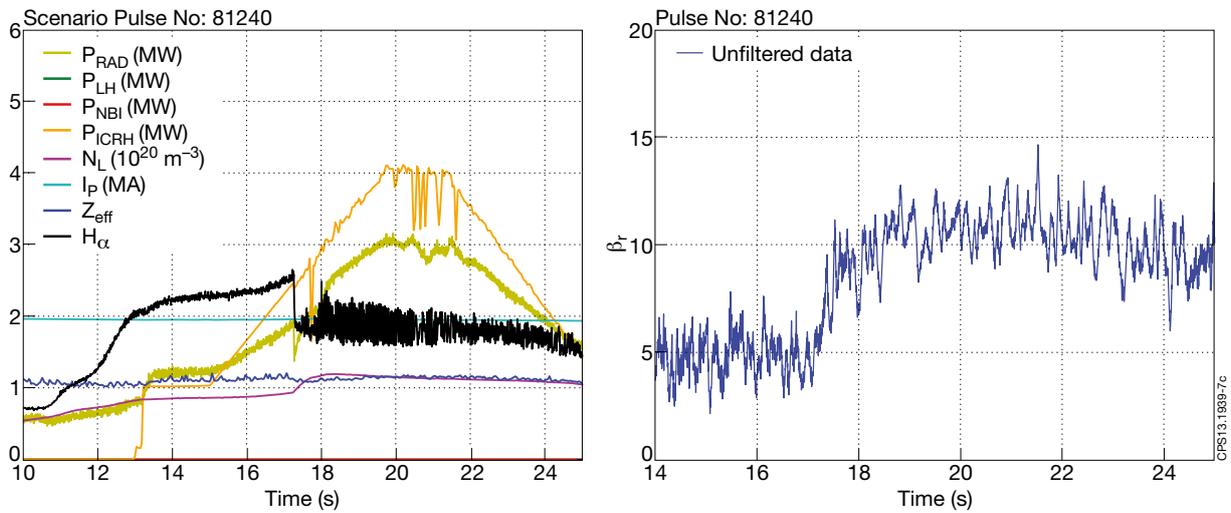


*Figure 7: Left) scenario of Pulse No: 81240, L- H mode transition , ICRF heating. Right) value of $\beta_r$ calculated during the additional heating phases.*
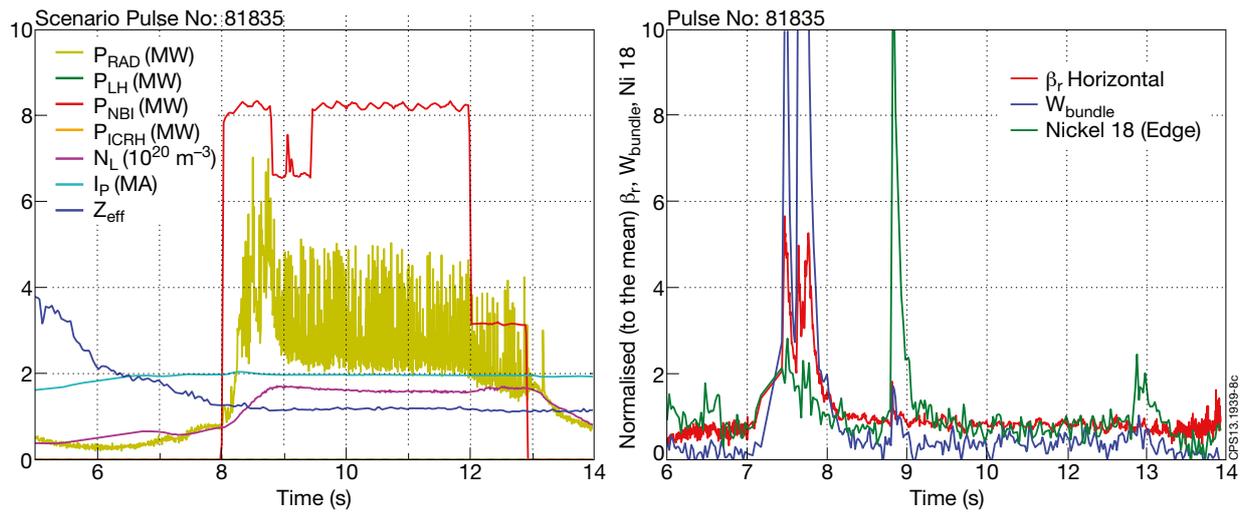
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*Figure 8: Left) scenario of Pulse No: 81835, H-mode transition, 8MW of NBI heating. Right) $\beta_r$, W line bundle and Ni XVIII line as a function of time during NBI phase. Data normalized to the same scale.*
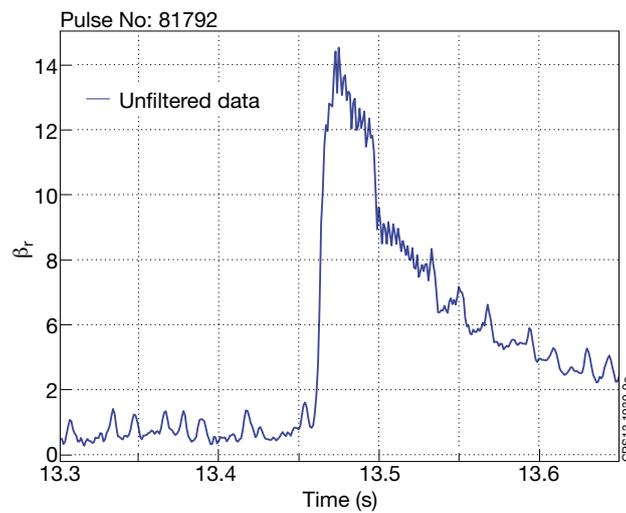


*Figure 9: $\beta_r$ as a function of time during a tungsten event, Pulse No: 81792. H-mode, 9.5MW NBI heating.*

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