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High radiation from intrinsic and injected impurities in Tore Supra ergodic divertor plasmas

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Abstract

We report experiments aimed at comparing several impurity mixtures (C, O, Cl, N, Ne, Ar) regarding their capability to reduce the power load on the divertor target plates. The divertor conditions required for each mixture to minimise the parallel power flux are determined, along with the resulting core effective charge $Z_{\rm eff}$ and volume averaged density. The radiation efficiency (ratio of edge radiation to plasma core contamination) of intrinsic carbon is found to increase with the total injected power. In the impurity injection experiments, nitrogen is found to be the best choice to reduce the power flux to the target plates: it has the same characteristics as C/O radiation (low core contamination), and it can be controlled. The low $Z_{\rm eff}$ observed in this case is attributed to the large value of the screening of the radiating ionisation stages of the impurity.

Keywords: Divertor radiation; Impurity screening; Power loading

1. Introduction

Reducing the power load on the divertor target plates to an acceptable value is one of the main issues of the next generation of tokamaks [1]. In Tore Supra, it is investigated in L-mode ohmic and radio frequency heated ergodic divertor (ED) plasmas through a series of experiments in which the divertor electron temperature ($T_{\rm e}^{\rm div}$) is chosen as control parameter [2]. Power load reduction is achieved either in high density low divertor temperature plasmas through intrinsic impurity radiation, or through purposely injected impurity radiation. In the latter case, a crucial issue is to optimise the divertor radiation while maintaining a low dilution of the plasma core ($Z_{\rm eff} < 1.6$ is required for ITER conditions). When ion cyclotron resonance heating (ICRH) is used in the ED configuration, ICRH antennas are located in the divertor volume. Good power coupling, generally, requires attached plasma conditions to be maintained, with a divertor temperature ranging from 25 to 10 eV. In this paper, several impurity mixtures (C, O, Cl, N, Ne, Ar) are compared regarding their capability to de-couple the divertor and core plasma conditions. The divertor conditions required for each mixture to minimise the parallel energy flux $Q_{\parallel}$ are determined, along with the resulting parameters of the plasma core, namely central dilution and electron density. Previous experiments done on Tore Supra with the aim of optimising the radiative divertor regime were reported in Ref. [3].

2. Experiment

Two series of experiments are reported in this paper. The first series, used to analyse the intrinsic impurity (C, O, and occasionally Cl) radiation and core contamination, consists of high density deuterium pulses with no impurity seeding. In the second series, N, Ne, or Ar are

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injected into the plasma. In the two series, the standard resonant ergodic divertor configuration is used: $B_t = 3.1$ T, $I_p = 1.4$ MA, $R = 2.39$ m, edge safety factor $q_\psi(a) \approx 3$. The current in the ED coils is set to its maximum value, 45 kA, corresponding to an average magnetic perturbation $\langle \delta B \rangle / B = 1.5 \times 10^{-3}$. The total injected power (P_{tot}) is up to 6.5 MW, obtained using 5 MW of ICRH in the minority heating scenario and 1.5 MW of ohmic heating. An electron density ramp-up is achieved with feedback control of the deuterium gas injection on the divertor electron temperature [2], or on the degree of detachment [4]. The range of T_e^{div} allowing good ICRH coupling is 25–10 eV ($T_e^{div} > 25$ eV is also achievable, but in ohmic pulses). The divertor electron density obtained by this technique increases with the total injected power, from 0.5×10^{19} m^{-3} at $P_{tot} = 1.5$ MW to 2.0×10^{19} m^{-3} at 6 MW for $T_e^{div} \approx 18$ eV. In impurity seeding experiments, the same feedback control of D_2 gas injection is used, with, in addition, a pre-programmed impurity puff.

The electron temperature and density on the neutralizer plates are measured by a set of dedicated fixed Langmuir probes with a fast data acquisition system. The parallel power flux to the target plate is calculated by $Q_\parallel = \gamma n_e T_e^{3/2}$. The radiated power is measured by bolometer camera arrays spanning a poloidal plasma cross-section from a midplane port. However, this poloidal array is located toroidally between two ED coils. As a result, the power balance equation is not always straightforward to verify, P_{rad} being often underestimated [5]. The radial emissivity profiles of the dominant radiating species are measured by a vibrating mirror VUV spectrometer: NV (123.9 nm), NeVIII (77.0 nm), CIII (97.7 nm) and OV (63.0 nm). The neutral carbon flux on the target plates is deduced from an absolutely calibrated visible imaging system viewing an entire neutralizer plate [6]. The contamination of the plasma core is estimated from the measurement of the effective charge by visible bremsstrahlung [7].

3. Intrinsic impurities

The total radiated power and the plasma core contamination obtained from intrinsic impurities (no seeding) are plotted versus the target plate electron temperature, Fig. 1, for a low divertor density case, $n_e^{div} = 0.5 \times 10^{19}$ m^{-3}. Two regimes are observed, depending on the divertor temperature value. For $T_e^{div} > 15$ eV, the radiated power and core contamination decrease with decreasing divertor temperature. This is correlated to a decreased neutral carbon flux measured on the target plate by the visible imaging system [6], governed by a decreased carbon sputtering rate. For $T_e^{div} < 15$ eV, the plasma is close to detachment. Although the neutral carbon flux measured on the target

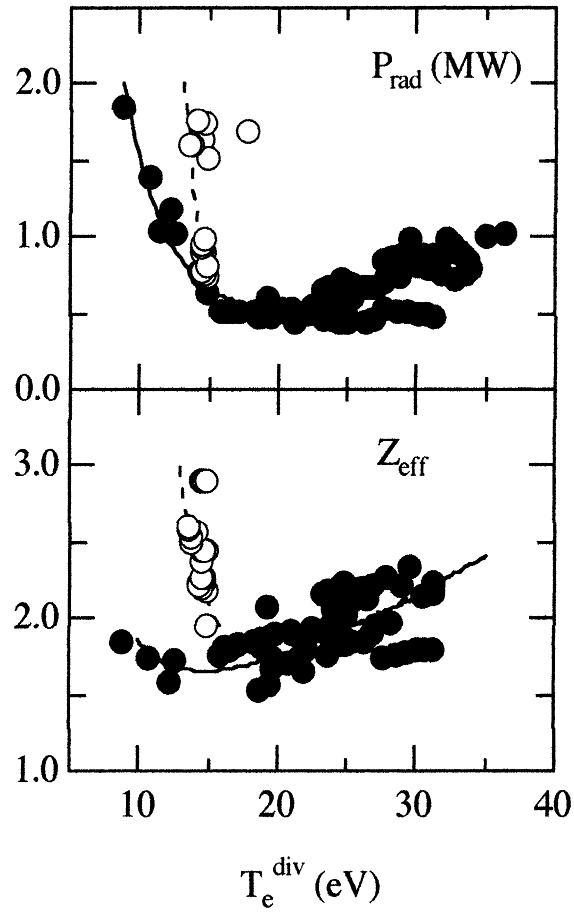

Fig. 1. Radiated power (P_{rad}) and core contamination (Z_{eff}) versus divertor electron temperature for intrinsic impurity scenario. $T_e^{div} > 15$ eV: regime controlled by carbon sputtering. $T_e^{div} < 15$ eV, solid line: C/O mixture alone. $T_e^{div} < 15$ eV, dashed line: C/O/Cl mixture.

plates continues to decrease, the radiated power increases sharply with decreasing temperature, and two branches are found, depending on the level of chlorine in the plasma. These two branches are also observed in Z_{eff}. When the plasma is free of chlorine (C and O only, full symbols fitted with solid lines in Fig. 1), high P_{rad} and low Z_{eff} are achieved for 8 eV $< T_e^{div} <$ 15 eV. In some cases however, chlorine is observed, and the high radiation level is accompanied by high core dilution (open symbols fitted with dashed lines in Fig. 1). Fig. 2 shows the radiation efficiency $P_{rad}/(Z_{eff} - 1)$ of this C/O/Cl mixture versus the control parameter T_e^{div}, for two values of the divertor density, $n_e^{div} = 0.5 \times 10^{19}$ m^{-3} (circles) and 1.5×10^{19} m^{-3} (triangles). At given divertor density, the T_e^{div} scan corresponds to a variation of P_{tot} in the data base. At low divertor density, the C/O mixture (full circles) produces a high radiation efficiency of about 2.2 MW for $T_e^{div} \approx 8$ eV, whereas the case with Cl (open

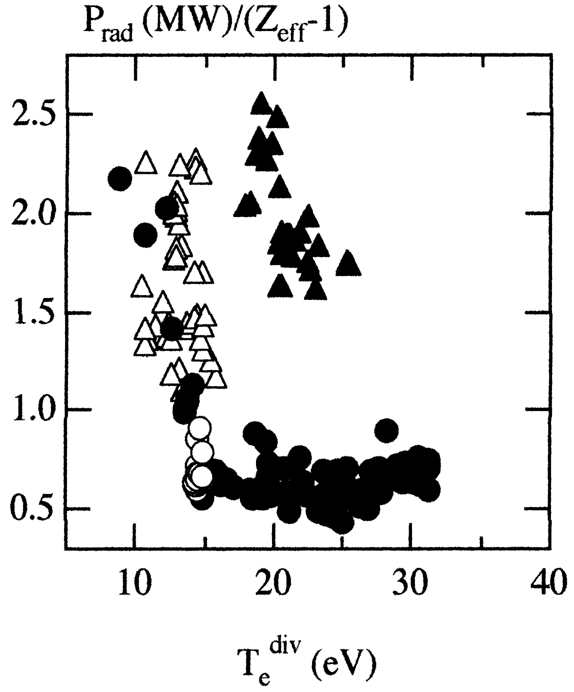

Fig. 2. Radiation efficiency versus divertor electron temperature. Circles: $n_e^{div} = 0.5 \times 10^{19}\ m^{-3}$. Triangles: $n_e^{div} = 1.5 \times 10^{19}\ m^{-3}$. Open (full) symbols: C/O/Cl(C/O) mixture.

circles) produces $P_{rad}/(Z_{eff} - 1) < 1$ MW for $T_e^{div} \approx$ 15 eV. At high divertor density (triangles on Fig. 2), a significant enhancement of the radiation efficiency of the intrinsic mixture is observed, compared to the lower divertor density case, for $T_e^{div} > 15$ eV. For $T_e^{div} > 15$ eV, C is the dominant impurity (measured from spectroscopic decomposition of P_{rad} and Z_{eff}). P_{rad} and Z_{eff} are controlled by T_e^{div}, through the level of carbon sputtering. The radiation efficiency is higher at higher divertor density (or, equivalently, higher injected power), because of reduced carbon penetration and increased radiation. For $T_e^{div} < 15$ eV, the production of carbon is very low. However, the radiation per carbon atom is increased [8], which produces the steep increase of $P_{rad}/(Z_{eff} - 1)$ with dropping T_e^{div} at low divertor density. At higher n_e^{div}, and for $T_e^{div} < 15$ eV, the contribution of O, and sometimes Cl, to P_{rad} and Z_{eff} becomes significant, and considerably complicates the interpretation of the measured radiation efficiency of the intrinsic mixture.

4. Injected impurities

4.1. Experimental results

In this section, the parallel power flux reduction achieved through nitrogen, neon or argon injection is analysed, and compared to that obtained at low divertor temperature with the intrinsic C/O mixture (free of chlorine). Attached plasma conditions are generally maintained ($T_e^{div} > 10$ eV), except in the nitrogen injection experiment where a feedback loop on the degree of detachment is used, and steady state detached operation is achieved. The plasma core contamination measured in each case for a given $Q_\parallel$, and a total injected power of 5 MW is reported on Fig. 3. The lowest achieved power flux onto the divertor target plates is about the same, $\approx 2.5\ MW/m^2$, whether nitrogen, neon or argon is used. It is about half that obtained from intrinsic impurities. However, different responses are observed regarding the corresponding central dilution. Indeed, while, the plasma response to the nitrogen injection is very close to that obtained from intrinsic C/O radiation alone (low $Z_{eff} \approx 2.3$), neon and argon injections produce a high central dilution ($Z_{eff} \approx 3.5$ and 4.5, respectively). The divertor temperature corresponding to the lowest $Q_\parallel$ is around 12 eV in each case, and the divertor density is around $0.6 \times 10^{19}\ m^{-3}$ for injected impurities, and a factor 2.5 higher for the intrinsic mixture. Interestingly enough, the resulting core density is much higher in the case of nitrogen radiation ($\langle n_e \rangle = 4 \times 10^{19}\ m^{-3}$) than in the case of neon or argon radiation ($\langle n_e \rangle = 2.5 \times$

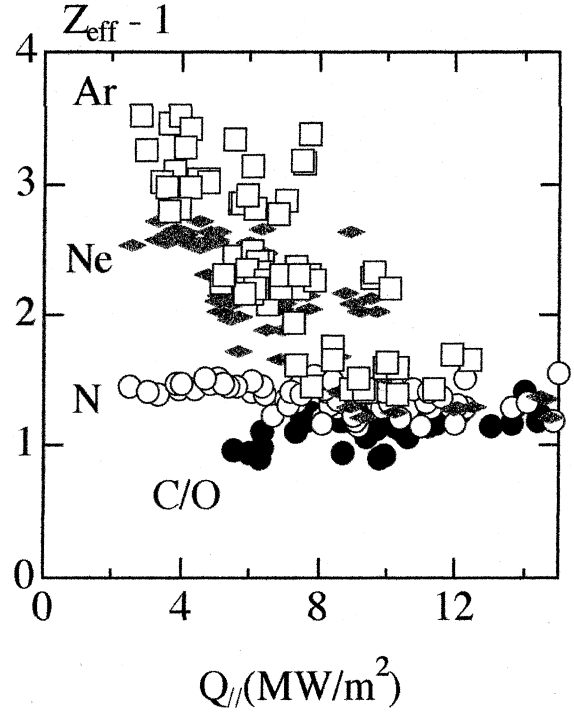

Fig. 3. Contamination of the plasma core produced by different impurity species to achieve a given parallel power flux to the target plates. $P_{tot} = 5$ MW. Full circles: intrinsic C/O mixture. Open circles: nitrogen injection. Full diamonds: neon injection. Open squares: argon injection.

10^{19} m^{-3}). In a first analysis, this rather high core density might be the reason of the low core dilution observed for nitrogen. Note that the values achieved for $Q_{\parallel}$ in these experiments are very low: they correspond to a factor of ≈ 5 reduction compared to lower density conditions with $T_e^{div} \approx 25$ eV.

4.2. Model for impurity radiation in a region of parallel transport

The experimental data of Fig. 3 have been analysed through the power balance model developed in [3,9–11]. The parallel heat flux on the divertor target plates ($Q_{\parallel 0}$, abscissa of Fig. 3) is linked to the incident parallel heat flux at the separatrix ($Q_{\parallel 1}$) by the relation:

$$Q_{\parallel 1}^2 - Q_{\parallel 0}^2 = 2P_e^2 c_{z,0} \kappa_0 \int_{T_0}^{T_1} T_e^{0.5} L_Z(T_e)\, dT_e, \quad (1)$$

where P_e is the electron pressure, $c_{z,0}$ the impurity concentration in the divertor volume, κ_0 the parallel heat conductivity and $L_Z(T_e)$ is the impurity radiative power loss coefficient. T_1 and T_0 are the electron temperature at the last closed magnetic surface and at the target plate, respectively. $Q_{\parallel 1} = (P_{tot} - P_{rad}^{core})/(2\pi a \Delta_{erg}/q_{edge})$, where P_{rad}^{core} is the power radiated inside the separatrix, a the plasma minor radius, Δ_{erg} the width of the ergodic layer (0.15 m), and $q_{edge} \approx 3$ is the edge safety factor. P_{rad}^{core} is evaluated for each impurity species from the radial emissivity profile of the dominant radiating ion, $P_{rad}^{core} = P_{rad}^{tot} \times (\int_0^{r_{sep}} \varepsilon\, dr / \int_0^a \varepsilon\, dr)$, Fig. 4. Nitrogen radiation is almost entirely located in the divertor volume, whereas argon radiation is mainly located in the core region, and that of neon stands in between. Fast impurity transport ($\tau_{\parallel} \approx 0.1$–1 ms) compared to the time to reach coronal equilibrium is assumed to compute $I(T_0) = \sqrt{\int_{T_0}^{T_1} T_e^{0.5} L_Z(T_e)\, dT_e}$. $I(T_0 = 10\ \text{eV})$ is plotted versus $n_e\tau_{\parallel}$ for C, N, Ne and Ar on Fig. 5. Radiated power predicted for a given divertor temperature increases significantly compared to coronal equilibrium values when rapid impurity transport is achieved. $\tau_{\parallel}$ is calculated by $\tau_{\parallel} = L/c_s, L = E_0/Sn_e \sin(\alpha)$ being the distance along a field line from the ionisation point to the target plate, and c_s is the ion acoustic velocity. E_0 is the energy of the impurity neutral, S its ionisation rate coefficient, and α is the angle between the target plate and the field line. In our experiments, E_0 is not measured. Therefore it is taken as a free parameter determining the value of $n_e\tau_{\parallel}$. $c_{z,0}$ is also not measured in our experiments; only the contamination of the central plasma region is measured by$Z_{eff} = 1 + Z(Z-1)c_{z,1}$, where $c_{z,1}$ is the impurity concentration in the confined plasma. Therefore, to compare Eq. (1) to the experimental data, we have defined an impurity screening factor $f_{sc} = c_{z,0}/c_{z,1}$, and we have replaced $c_{z,0}$ by $f_{sc}(Z_{eff} - 1)/Z(Z-1)$ in Eq. (1). This screening factor represents the ratio of the impurity concentration in the region where it radiates to the impurity concentration in the core. This 'radiation compression' factor departs from the standard impurity enrichment factor [12–14] insofar that only the radiating impurities are considered in determining the boundary density, irrespective of neutral impurity density. The computed screening factor and the corresponding ionisation length of neutral atoms, for C, N, Ne, and Ar are shown on Fig. 6. It indicates that the screening factor depends very weakly on E_0. It is high, respectively close to 10 and 5 for the nitrogen injection experiment and for intrinsic carbon radiation. On the

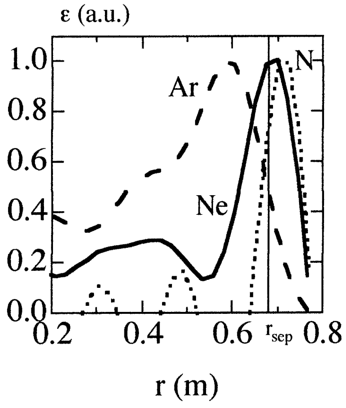

Fig. 4. Radial emissivity profiles of the dominant radiating species, for nitrogen, neon, and argon injection experiments. Full line: NeVIII (77.0 nm). Dashed line: ArXVI (35.4 nm). Dashed dotted line: NV (123.9 nm).

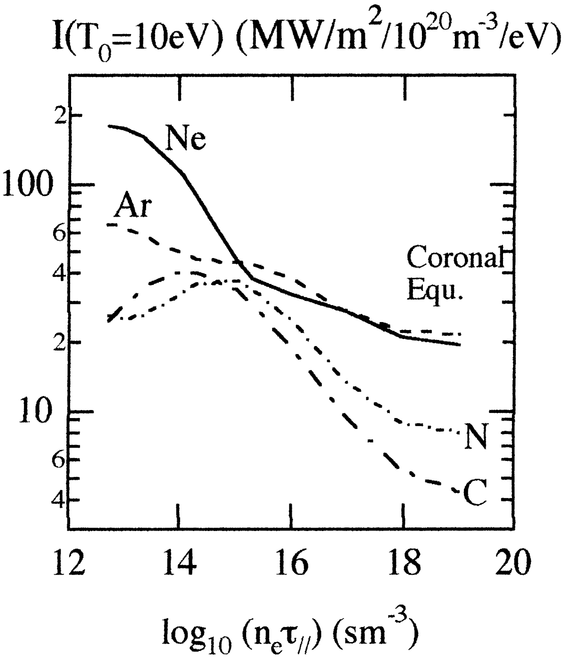

Fig. 5. Calculation of the integral $I(T_0 = 10\ \text{eV})$ versus $n_e\tau_{\parallel}$.

contrary, the screening factor of neon and argon is low, between 1 and 2. For argon this is due, despite the short ionisation length of Ar neutrals, to the fact that argon radiates mainly in the plasma core. For neon, no screening is found since Ne neutrals are mainly ionised in the confined plasma ($\lambda_i^{\mathrm{Ne}} > \Delta_{\mathrm{erg}}$) and hence hardly radiate in the divertor volume. The compression of carbon and nitrogen radiation in the divertor region is high. This is associated to $\lambda_i^{\mathrm{C,N}} < \Delta_{\mathrm{erg}}$. Moreover, for these impurities, the improvement in radiation due to rapid impurity transport is high. The result is a high radiation level, and a low core contamination. On the contrary, the radiation compression of neon and argon is very low, and there is almost no gain in radiation compared to coronal equilibrium. The result is a high dilution of the plasma core. The conclusion is that nitrogen is the best choice to reduce the power flux to the target plates: the resulting contamination of the plasma core is only slightly higher than that due to intrinsic impurity radiation, and the advantage of nitrogen compared to intrinsic impurities is that its injection can be controlled.

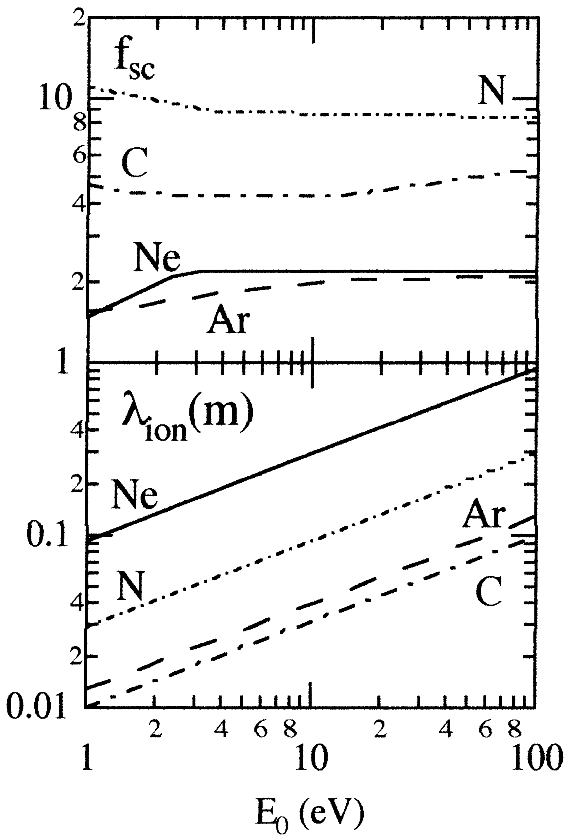

Fig. 6. (a) Screening factor deduced from the power balance model, versus the energy of the incoming neutrals in the experiments with intrinsic C/O mixture (labelled C, dashed dotted line), nitrogen (N, dashed dotted), neon (full line), and argon injection (dashed line). (b) Corresponding ionisation length of the neutral atoms.

5. Conclusion

Experiments aimed at reducing the parallel power flux to the target plates in ohmic and ICRH ED plasmas have been reported. In the case of the intrinsic impurity mixture, two radiation regimes are found, depending on the divertor temperature. For $T_e^{\mathrm{div}} > 15$ eV, the divertor radiation and core contamination are controlled by the level of carbon sputtering. The radiation efficiency increases with the injected power. For $T_e^{\mathrm{div}} > 15$ eV, the level of C sputtering is very low, which allows O and sometimes Cl to take an increasing part in the radiation and core contamination, despite an increased radiation per C atom. The result, in the case of pure C/O mixture radiation is a low $Q_{\parallel}$, around 5 $\mathrm{MW/m^2}$, and a low core contamination. In the case of N, Ne or Ar radiation, even lower $Q_{\parallel}$ are achieved, 2.5 $\mathrm{MW/m^2}$, but with different responses regarding the corresponding plasma core contamination ($Z_{\mathrm{eff}} = 2.3, 3.5$ and 4.5, respectively). The radiation compression factor of N and C is high, and for these two impurities, the gain in radiation due to rapid impurity transport is high. On the contrary, no compression of the radiation in the divertor volume is found for Ne and Ar. For Ne, this is due to a neutral ionisation length larger than the width of the ergodic layer. On the other hand, Ar neutrals are ionised well inside the divertor volume, but the radiating Ar ions are located much further inside the separatrix. The conclusion is that nitrogen is the best choice to reduce the power flux to the target plates.

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