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On the relation between radiation level, central impurity concentration and helium exhaust in a burning fusion plasma

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Abstract

For a stationary burning fusion plasma a relation is derived and discussed which describes the close link between energy confinement, He-exhaust efficiency, central impurity density and the corresponding radiation level from impurities at the plasma boundary. Such a coherent approach helps to identify crucial parameters. Possibilities for further optimization are deduced from scalings of the radiation level with respect to the electron density, transport coefficients, impurity charge Z and He-exhaust efficiency.

Keywords: Radiation cooling; Steady-state fusion; He-exhaust; Impurity seeding

1. Introduction

In recent tokamak experiments it has been shown that impurity seeding (e.g. neon) can provide significant line radiation from the plasma boundary which allows to distribute nearly all the heating power quasi-stationary on large areas without loosing the good energy confinement properties [1-3]. This concept of a cold radiative plasma edge might be a solution for the power exhaust problem of future fusion devices like ITER. However, in a fusion reactor several conditions have to be fulfilled simultaneously. After ignition the plasma can only be maintained burning if the impurity level in the centre stays sufficiently low. This comprises intrinsic and seeded impurities as well as the helium ash. Corresponding predictions for next step devices like ITER are of utmost importance. In this respect several attempts are made: scaling of experimental data like Z_{eff} [4], identification of a figure of merit for the radiation efficiency [5], discussion of conditions for a stationary burning plasma depending on He-exhaust [6], calculation of the ignition margin for various levels and types of impurities [7] and calculations of the radiation level expected for various impurity species and transport parameters [8-10]. However, a coherent approach taking into account all aspects is still missing.

In this paper we will contribute to such a coherent approach by deriving a relation which describes the link between the radiation level and the maximum impurity concentration based on a simple but adequate parametrization. The energy confinement will be described by the confinement time τ_E and for the radiated power P_{rad} we will use a parametrization based on the impurity flux and therefore also on the particle confinement τ_z of the impurity species with charge Z. The radiation characteristics are taken from experimental data obtained on TEXTOR 94 and model calculations with the transport code RITM [11], which can describe plasmas with a high radiation level self-consistently.

The ultimate aim of a coherent approach should be the identification of the most important parameters which then allow to find the optimum impurity scenario (wall materials, coatings, seeded impurities) for a fusion reactor. For this purpose the rather subtle balance between the benefits of a high radiation level at the edge and the disadvantages due to radiation losses from the centre and fuel dilution has to be understood. In this respect the relations being derived serve to describe the scaling of the radiation level with Z, electron density n_e, helium exhaust efficiency, power density and transport parameters.

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2. Conditions for steady state burn

For a stationary burning plasma the balance between the heating power density from α-particles $P_\alpha = \frac{1}{4}(n_{\mathrm{DT}}^2)\langle\sigma v\rangle_{\mathrm{fus}} E_\alpha$ (with density of deuterium + tritium n_{DT}, the rate coefficient of the fusion process $\langle\sigma v\rangle_{\mathrm{fus}}$, energy of α-particles E_α) and the power loss has to be fulfilled. This balance is influenced by impurities which can reduce P_α via a reduction of n_{DT} (= fuel dilution) and which may provide significant radiation from the plasma centre. The *fuel dilution* due to helium ash n_{He} and other impurities of charge Z and density n_Z with an electron density n_e is given by $n_{\mathrm{DT}} = n_\mathrm{e} - 2n_{\mathrm{He}} - Zn_z$, or in terms of concentrations $c_{\mathrm{DT}} = 1 - 2c_{\mathrm{He}} - Zc_i$. The total energy content is then given by $E = \frac{3}{2}T(n_\mathrm{e} + n_{\mathrm{DT}} + n_{\mathrm{He}} + n_z)V_E$ or $E = 3n_\mathrm{e}T\eta V_E$ introducing a dilution factor $\eta = 1 - \frac{1}{2}(c_{\mathrm{He}}) - \frac{1}{2}(Z-1)c_z$ and the effective 'energy volume' V_E. In the following we assume that all particles have the same temperature T.

The relation between P_α and E is described by the *energy confinement time* τ_E. We have to distinguish the α-particle heating P_α and the net heating power $P_{\mathrm{heat}} = P_\alpha - P_\mathrm{R}$ taking into account *central* radiation losses P_R due to bremsstrahlung and line radiation from impurities. From this we obtain two distinct definitions: $E/V_E = P_\alpha\tau_{\mathrm{E1}}$ and $E/V_E = P_{\mathrm{heat}}\tau_{\mathrm{E2}}$, where only τ_{E1} includes the central radiation losses ($\tau_{\mathrm{E1}} < \tau_{\mathrm{E2}}$). The total heating power is given by $P_{\mathrm{heat,tot}} = P_{\mathrm{heat}}V_E$. Under steady state conditions the fusion rate (= production rate of α-particles) must equal the exhaust rate of the He-particles. *He-exhaust* can be parametrized by introducing the effective confinement time $\tau_{\mathrm{He}}^* = \tau_{\mathrm{He}}/(1-R)$, where τ_{He} is the confinement time for He and R is the recycling coefficient ($\varepsilon = 1 - R$ is the exhaust efficiency determined by scrape-off layer physics and pumping capabilities). The relation $n_{\mathrm{He}}/\tau_\mathrm{e} = \frac{1}{4}(n_{\mathrm{DT}}^2)\langle\sigma v\rangle_{\mathrm{fus}}$ has to be fulfilled. Replacing the fusion rate by the heating power we obtain

$$n_{\mathrm{He}} = \frac{E}{E_\alpha V_E}\frac{\tau_{\mathrm{He}}^*}{\tau_{E1}}. \qquad (1)$$

Thus, not τ_{He}^* but the ratio $\rho_{\mathrm{He1}}^* = \tau_{\mathrm{He}}^*/\tau_{E1}$ defines the He-level. This also holds for the ratio $\rho_{\mathrm{He2}}^* = \tau_{\mathrm{He}}^*/\tau_{E2}$. The relation between these two ratios is $\rho_{\mathrm{He2}}^* = \rho_{\mathrm{He1}}^*(1 - P_R/P_\alpha)$. In the following we will use $\rho_{\mathrm{He}}^* = \rho_{\mathrm{He2}}^*$ only.

3. The maximum impurity concentration from steady state solutions

Solutions for Eq. (1) have to be found. In order to restrict the solutions to a parameter range expected e.g. for ITER-like plasmas we used a given value for the triple product $n_\mathrm{e}\tau_{E2}T$, with the consequence that T is not anymore a free parameter. For a certain c_z and ρ_{He}^* we can obtain two solutions, as is shown in Fig. 1 for $n_\mathrm{e}\tau_{E2}T = 10^{22}$ keV s/m^3. The two solutions (high and low T corresponding to stable and unstable solutions, respectively) coincide when approaching the maximum impurity concentration $c_{z,\mathrm{max}}$. Beyond this value no steady state solution is possible.

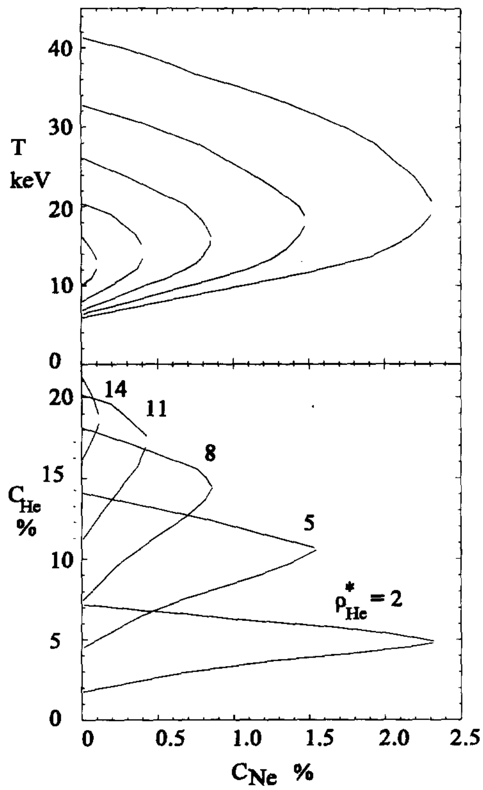

Fig. 1. Solutions for a stationary burning fusion plasma at a given $n\tau_{E2}T = 10^{22}$ keV s/m^3 and various He-exhaust parameters ρ_{He}^*.

A summary of $c_{z,\mathrm{max}}$ values for various Z as a function of ρ_{He}^* is shown in Fig. 2a. In a real fusion plasma we have to expect a certain level of intrinsic impurities which may not help for radiation cooling but will contribute to fuel dilution. For illustration a constant level of 2% of Be has been assumed in addition to the impurities for which $c_{z,\mathrm{max}}$ is computed (see Fig. 2b). A significant reduction of the $c_{z,\mathrm{max}}$ values results. The solutions are only sensitive on $n_\mathrm{e}\tau_{E2}T$ for low values of the triple product. In the range of $n_\mathrm{e}\tau_{E2}T \approx 10^{22}$ keV s/m^3 we find that $c_{z,\mathrm{max}} \sim (n_\mathrm{e}\tau_{E2}T)^{0.4}$. At higher values ($> 4 \cdot 10^{22}$ keV s/m^3) this dependence diminishes.

The data in Fig. 2 clearly demonstrate that $c_{z,\mathrm{max}}$ depends strongly on Z. In the dilution limited case ($Z \approx 10$ and $\rho_{\mathrm{He}}^* \approx 5$–$10$) we find $c_{i,\mathrm{max}} \sim Z^{-2.3}$, whereas in the radiation limited case at high Z the scaling approaches $\sim Z^{-3}$. An important question is now to what extent the reduction of $c_{z,\mathrm{max}}$ with increasing Z can be compensated

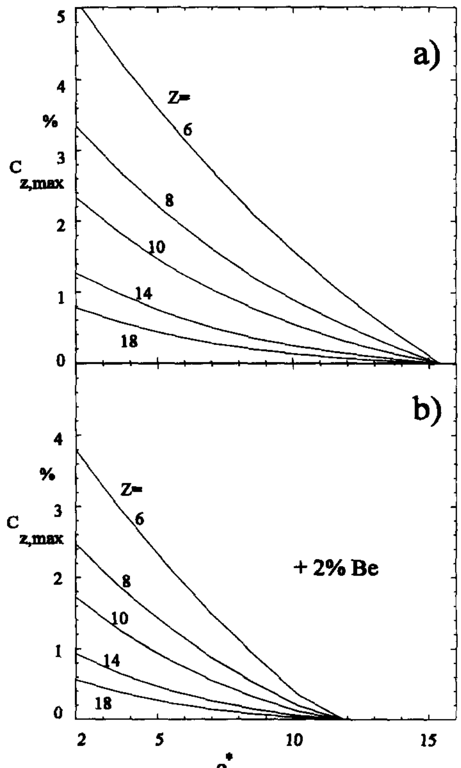

Fig. 2. Maximum impurity density for stationary conditions and various Z as a function of the helium exhaust parameter; (a) without and (b) with an additional level of 2% beryllium ($n\tau_{E2}T = 10^{22}$ keV s/m^3).

by a higher radiation efficiency of the heavier impurities at the plasma boundary?

4. The radiation potential

We will use an expression for impurity radiation from the plasma boundary which allows to relate it to the particle confinement time. Based on the fact that low and medium Z impurities will mainly radiate from the plasma boundary we need only to know the total radiation irrespective of their spatial distribution or specific wavelengths which are emitted. The total number of excitations per ion species i into the level j is given by the ratio of rate coefficients for excitation and ionization

$$n_{\rm ex}^{ij} = \langle \sigma v \rangle_{\rm ex}^{ij} / \langle \sigma v \rangle_i = f(T_{\rm e}). \quad (2)$$

After multiplication with the excitation energy E_{ij} and summation over all charge states i and excitation levels j we obtain the total energy radiated during the life time (dwell time) of a single particle in the plasma (radiation potential)

$$E_{\rm rad} = \sum_i \sum_j \xi_i n_{\rm ex}^{ij} E_{ij}. \quad (3)$$

The coefficients ξ_i represent the relative population of ionization stages. The total radiation can be calculated by multiplication with the total impurity flux Γ_z entering the plasma

$$P_{\rm rad,tot} = E_{\rm rad} \Gamma_z. \quad (4)$$

High values for $E_{\rm rad}$ can only be achieved if the life time (= ionization time) of the various charge states, in particular the Be- and Li-like ones, are long enough to allow for sufficient excitation processes. This is true below a certain $T_{\rm e,critical} \approx E_{\rm i}/2$, where the ionization time of a given charge state with an ionization energy $E_{\rm i}$ is $\tau_{\rm i} = 1/(n_{\rm e}\langle \sigma v \rangle_{\rm i})$. Therefore, $T_{\rm e}$ at the plasma boundary plays a crucial role. Normally we assume that the impurities start as neutrals at or close to the separatrix (limiter case). $E_{\rm rad}$ is then the ratio of the total radiation to the total flux of neutrals. But also for particles starting as neutrals at the wall and being partly ionized before crossing the separatrix the radiation potential may be a useful term. In this case $E_{\rm rad}$ is given by the ratio of the total radiation inside the confined volume and the particle flux crossing the separatrix. As an example we considered a case where neon is transported radially along a certain $T_{\rm e}$-profile and calculated (RITM) for the various radii r the ratio of the total radiation inside r and the inward particle flux (of lower ionization states) crossing r. The result shown in Fig. 3 exhibits that below $T_{\rm e,critical} = T_{\rm e}(a) \approx 150$ eV the $E_{\rm rad}$ values are close to their optimum of 25–50 keV. The relative maximum of $E_{\rm rad}$ appears where the ionization distribution contains the maximum of strongly radiating species (Li- and Be-like states). For other impurities we obtain the following values: Si, $T_{\rm e,critical} < 300$ eV; Ar, $T_{\rm e,critical} < 600$ eV.

Also in cases in which the life time of the various states is limited by parallel transport rather than by ionization (e.g. in the SOL) the radiation potential is a useful term, but the calculation has to be modified resulting in smaller values for $E_{\rm rad}$. However, for the further discussion we only consider radiation inside the confined volume where the radial transport dominates and $T_{\rm e} < T_{\rm e,critical}$. With these

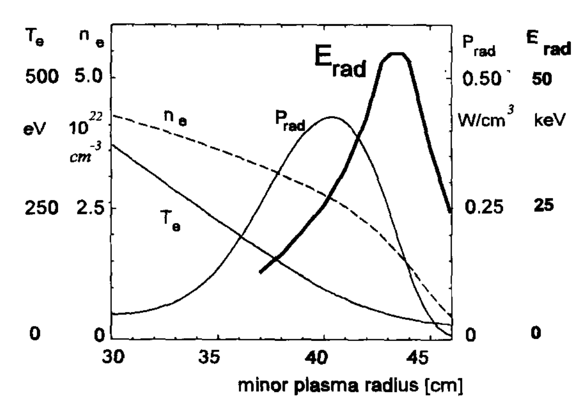

Fig. 3. Radiation potential $E_{\rm rad}\,(<r) = P_{\rm rad,tot}(<r)/\Gamma(r)$ for a neon flux Γ crossing the radius r; all neutrals start at $r = 46$ cm, $T_{\rm e} = 25$ eV.

restrictions we guarantee a general validity of the relations derived for limiter and divertor machines. It is important to note that $T_e(a)$ is not a free parameter since it depends largely on the radiation level itself. Thus a self-consistent treatment of the problem is required in transport calculations e.g. as it is done in the RITM code.

According to Eq. (4) the radiation level can be adjusted by choosing the proper impurity flux, but the upper limit is given by $c_{z,\max}$. Based on the definition of the radiation potential we derive in the following a relation which describes the link between $c_{z,\max}$ and the radiation level.

5. The radiation level at the plasma boundary

The particle confinement time τ_z serves to relate the impurity density n_z to the total impurity flux Γ_z according to $\Gamma_z = V_z n_z / \tau_z$. Here we have introduced an effective volume V_z over which the impurities are distributed. Thus, we obtain for the total radiated power

$$P_{\mathrm{rad,tot}} = \frac{E_{\mathrm{rad}} n_e c_z V_z}{\tau_z}. \tag{5}$$

The radiation level can be expressed as

$$\gamma = \frac{P_{\mathrm{rad,tot}}}{P_{\mathrm{heat,tot}}} = \frac{E_{\mathrm{rad}} n_z V_z / \tau_z}{3 n_e T \eta V_E / \tau_{E2}}, \tag{6}$$

or by introducing the ratio $\rho_z = \tau_z / \tau_{E2}$ we get

$$\gamma = c_z \left[\frac{E_{\mathrm{rad}}}{3T\eta\rho_z} \frac{V_z}{V_E} \right]. \tag{7}$$

Inserting $c_{z,\max}$ into Eq. (7) we get $\gamma_{\max}$. The quality of predicting γ with this equation depends of course on the quality of the input parameters. We will discuss these parameters as obtained from the TEXTOR 94 experiment and extrapolate them to ITER-like plasmas. For the presentation of Eq. (7) we will plot γ versus the term in brackets and use c_z as a parameter (Fig. 4).

At a high radiation level the typical radiation potential for neon as determined in TEXTOR is $E_{\mathrm{rad}} = 30$ keV and is also used for the ITER-like plasma. Also the same profile factor $V_z / V_E = 2$ is taken. But we have to extrapolate τ_E and τ_z which determine ρ_z ($\rho_z \approx 0.2$ in TEXTOR for neon). From the ITER-L89-P scaling [12] we obtain a factor of 60 for τ_E. The increase of τ_z will be less. We derive a factor of 8 by taking into account geometry effects ($\tau_z \sim V/O$). Lower factors (e.g. 1.5) can be expected for higher plasma edge densities, but a precise scaling for τ_z is not available. Thus to obtain an estimate we chose a rather pessimistic scaling factor of 6 resulting in $\rho_z = 0.02$. With these numbers and $c_{z,\max}$ from Fig. 2 we have calculated the maximum radiation level as a function of ρ^*_{He}. For other impurities than neon (C, O, Si, Ar) we scaled E_{rad} according to $\sim Z^3$ (see Section 6). The resulting data points are indicated in Fig. 4 for (a) a plasma containing only helium and the impurity Z and (b) with an additional level of 2% of beryllium.

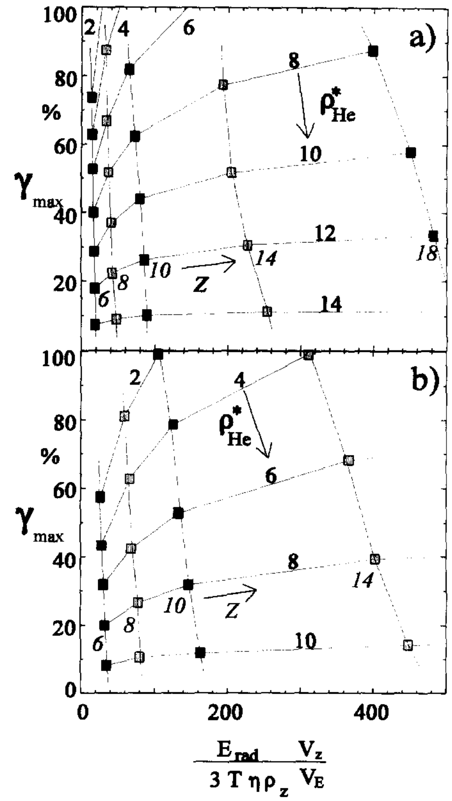

Fig. 4. Parametrization of the radiation level according to Eq. (7) based on $c_{z,\max}$ from Fig. 2 and parameters extrapolated from TEXTOR to ITER-like plasmas and various Z and ρ^*_{He}; (a) without and (b) with 2% of additional beryllium.

The very strong dependence of γ on the He-exhaust parameter ρ^*_{He} and the disadvantageous effect of additional Be is evident. According to these examples a high radiation level $\gamma > 0.8$ is only possible with neon for $\rho^*_{\mathrm{He}} < 6$ (or with Be $\rho^*_{\mathrm{He}} < 4$). In contrast to this strong dependence on ρ^*_{He} the improvement with Z turns out to be rather moderate — a consequence of the fact that the radiated power in the centre and at the edge scale similarly, in particular for higher Z.

The effect of different scalings or the influence on other variations of parameters can easily be derived from Eq. (7) or Fig. 4. For example, when assuming enhanced particle transport with a value of $\rho_z = 0.01$ instead of $\rho_z = 0.02$ the radiation level for neon with $\rho^*_{\mathrm{He}} = 10$ (no Be, Fig. 4a) increases from $\gamma = 0.45$ to $\gamma = 0.9$.

6. Optimization and scalings

The relation given in Eq. (7) is based on the parametrization of particle- and energy transport and radiation, thus has a general validity irrespective of the specific transport properties (or models). For further analysis and identification of the crucial parameters we will apply a simple particle transport model. A more sophisticated treatment of particle transport leads in most cases only to scaling factors (e.g. peaking factors) without a modification of the essential dependencies. In the simple model particle transport is described by *diffusion* only. The particle source is determined by the ionization length λ_i of the neutrals entering the plasma boundary. Inside the source free zone the impurity profile (summed over all charge states) is flat [13]. The particle confinement time is given by $\tau_z = (\lambda_i/D)(V_z/O)$, where O depicts the vessel surface and D is the diffusion coefficient. From this relation we can derive an expression for the total radiation per particle by integrating over the radiation from the different ionization shells of the impurity, the width of which is given by $\sqrt{D\tau_i}$, with the ionization time τ_i. The radiation potential then becomes [14]:

$$E_{rad} = \frac{\lambda_i}{\sqrt{D}} S \quad \text{with } S = \sum_i \xi_j \sqrt{n_e^j} \frac{L_j(T_e)}{\sqrt{\langle \sigma v \rangle_j^z}}. \tag{8}$$

The sum S over the different charge states j represents the atomic physics including the local values for the ionization rate coefficient $\langle \sigma v \rangle_j^z$, the radiation function $L_j(T_e)$ and the density n_e^j within the radiating shell. The factors ξ_j represent the effect of overlapping ion-shells. Based on this expression for E_{rad} we can derive a new formula for the radiation level

$$\gamma = c_z \sqrt{D}\, S\, n_e / P_{surf}. \tag{9}$$

P_{surf} is the power flow density normalized to the wall surface ($P_{surf} = P_{heat,tot}/O$). For ITER a power flow density in the range of $P_{surf} \approx 0.3$ MW/m^2 is expected, which is not too far from those values in present day machines (e.g. TEXTOR, ASDEX-U, JET: 0.14-0.19 MW/m^2). The product $\sqrt{D}\,S$ has a value of about 1500 keV m/s with the neon conditions described above for TEXTOR. For optimization of the radiation level we have to maximize the parameters on the right hand side of Eq. (9). This will be discussed in the following.

6.1. Z-scaling

The product $c_{z,max} S$ scales with $Z^{0.7}$ for the lower Z range. At higher Z the dependence becomes weaker. This follows from the scaling $S \sim Z^3$ [8] and the scaling for $c_{z,max}$ described in Section 3.

6.2. Electron density

γ increases proportional to n_e if the density in the radiating belt is kept constant. In case this edge electron density increases proportional to the central n_e, the additional density dependence of S leads to a $\gamma \sim n_e^{3/2}$ scaling. If in addition the electron temperature decreases and therefore the radiating shell extends to smaller radii, thus higher n_e, the scaling can become even stronger. For a more accurate scaling this non-linear dependence has to be treated self-consistently (e.g. with RITM). In any case, n_e is one of the parameters with the strongest influence on γ.

6.3. Peaking

The simple diffusion model considers only flat impurity density profiles. Any relative profile peaking would decrease the maximum γ. This can be taken into account by introducing peaking factors as it has been done implicitly with the ratio V_z/V_E in Eq. (7). For low Z elements such a peaking has not been observed so far, whereas accumulation of high Z impurities can occur, as has been observed under certain conditions with e.g. Mo and W [15].

6.4. Transport coefficients

Increased radial transport (D) of impurities would help to optimize the radiation level. An important example for such an improvement is given by the application of a distortion field at the plasma boundary to produce an ergodic layer. Such experiments on Tore Supra have demonstrated that more radiation can be achieved with less impurities in the plasma [16]. For example, assuming an increase of D by a factor of 4 would have the same effect as an improvement of the helium exhaust parameter from $\rho_{He}^* = 10$ to $\rho_{He}^* = 6$ (see Fig. 4a, neon).

7. Conclusions

For a stationary burning fusion plasma all aspects of energy and particle transport including He-exhaust, fuel dilution and line radiation from impurities at the plasma boundary have to be considered consistently. Relations have been derived which describe these links based on an adequate parametrization. These relations provide useful scalings and allow identification and discussion of crucial parameters. Among these the He-exhaust parameter ρ_{He}^* is most critical since it has a strong influence on the maximum radiation level. Predictions on the feasibility of a cold radiative plasma edge as a solution for the energy exhaust problem in the next step machine suffer still from significant uncertainties. However, the scalings offer various options for further optimization: enhanced particle transport at the plasma boundary (e.g. ergodic layer), heavier impurities than neon and operation at the highest n_e possible may provide enough margin for improvements.

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