Integrated core- SOL-divertor simulations of ITER H-mode scenarios with different pedestal density

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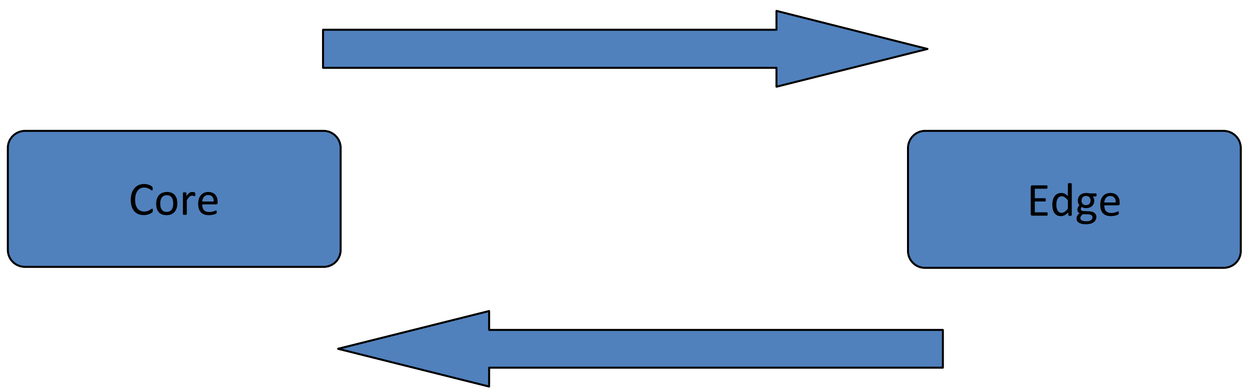
COREDIV = 1D transport in the core self-consistently coupled to 2D model in the SOL

INTERPLAY BETWEEN EDGE AND CORE

Interaction between bulk and edge plasma is a complex phenomena involving a lot of physics processes mostly through:

- **Energy balance**
- **Particle balance**

Changes to core confinement alters edge properties



Modification of edge properties affects core confinement

Equations and transport model for the core plasma - **Background ions**

1D transport of particles (n_i) and energy (T_e, T_i):

$$\frac{\partial n_i}{\partial t} + \frac{1}{rg_1}\frac{\partial}{\partial r}\left[rg_2\left(-D_i\frac{\partial n_i}{\partial r} + w_i n_i\right)\right] = S_i(r) = S_i^0 \times P(r) + neocl.\, contrib.$$

$$\frac{3}{2}\frac{\partial n_i T_i}{\partial t} + \frac{1}{rg_1}\frac{\partial}{\partial r}\left[rg_2\left(-k_i\frac{\partial T_i}{\partial r} + \frac{5}{2}\Gamma_i T_i\right)\right] = P_{AUX}^i + Q_{ei}$$

$$\frac{3}{2}\frac{\partial n_e T_e}{\partial t} + \frac{1}{rg_1}\frac{\partial}{\partial r}\left[rg_2\left(-k_e\frac{\partial T_e}{\partial r} + \frac{5}{2}\Gamma_e T_e\right)\right] = P_{OH} + P_{AUX}^e + P_\alpha - P_B - P_{cyc} - P_{lin} - P_{ion} - Q_{ei}$$

S_i^0 iterated to have constant $<n_e>$

Quasineutrality: $$n_e = n_i + \sum_{k,j} n_j^k \qquad < n_e >= const.$$ i=D,T

Equations for plasma rotation and plasma current neglected → j(r) – given input function

g_1, g_2 – metric coefficients

Transport model for background ions

Anomalous transport described by simple model:

τ_E from experimental ELMy H-mode scaling

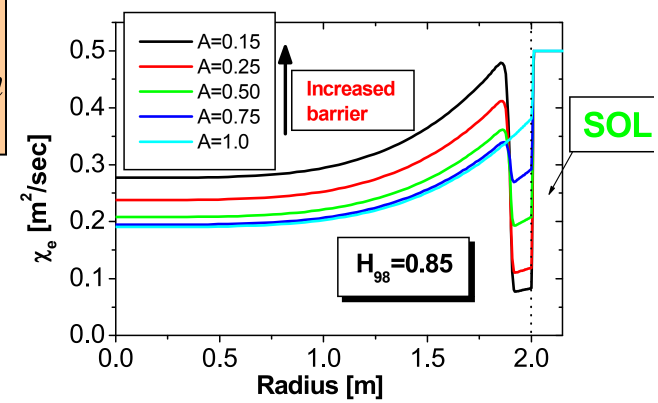
F(r) – profile function

$$F(r) = \left(1 + \left(\frac{r}{a}\right)^4\right)$$

$$\chi_e^{an} = C_e \frac{a^2}{\tau_E} F(r)$$

$$\chi_i^{an} = \chi_e^{an} \qquad D_i^{an} = 0.35\chi_e^{an}$$

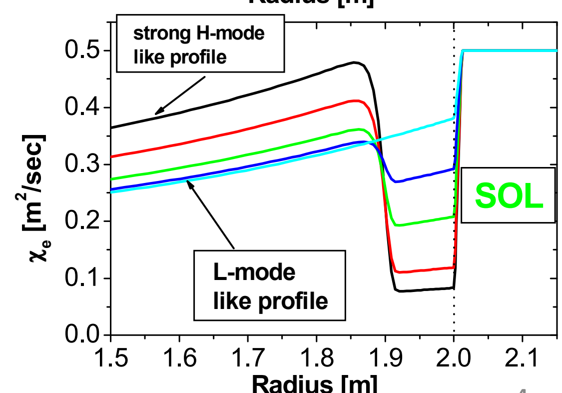
C_e – adjusted iteratively to keep prescribed confinement



In addition, neoclassical ion heat conductivity

$$\chi_i = \chi_i^{an} + \chi_i^{neo}$$

Anomalous pinch $V_{pinch}/D_i \sim r/a^2$



Core plasma

Impurity ions

- Different types of impurities are treated simultaneously and self-consistently

$$\frac{\partial n_j^k}{\partial t} + \frac{1}{rg_1}\frac{\partial}{\partial r}\left(rg_2\Gamma_j^k\right) = n_e\left[n_{j-1}^k\alpha_{ion,k}^{j-1} - n_j^k(\alpha_{ion,k}^j + \beta_{rec,k}^j) + n_{j+1}^k\beta_{rec,k}^{j+1}\right] \quad j = 1,\ldots Z_k$$

$$\Gamma_j^k = \Gamma_j^{nc,k} + \Gamma_j^{an,k}$$

High Z impurity accumulation

Pfirsch-Schlüter contribution

$$\Gamma_j^{nc} = -D_j^{PS,k}\partial n_j^k / \partial r + n_j^k W_j^{PS,k} = \left(1+q^2\right)\rho_k^2 \nu_j^k \left[-\frac{\partial n_j^k}{\partial r} + Z_j\left(\frac{1}{n_i}\frac{\partial n_i}{\partial r} - \frac{1}{2T_i}\frac{\partial T_i}{\partial r}\right)\right]$$

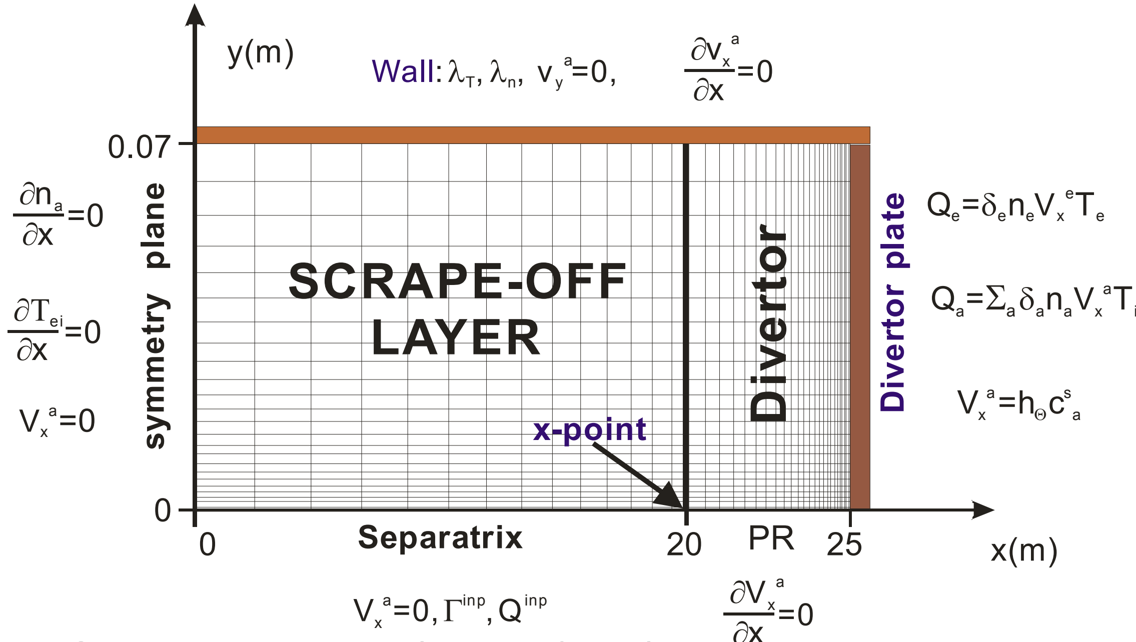
Anomalous contribution

$$\Gamma_j^{an,k} = -D_j^{an,k}\partial n_j^k / \partial r + n_j^k V_j^{pinch,k} \qquad V_j^{pinch,k} \propto -D_j^{an,k} r / a^2$$

Usually anomalous transport same as for background plasma (ambipolarity)

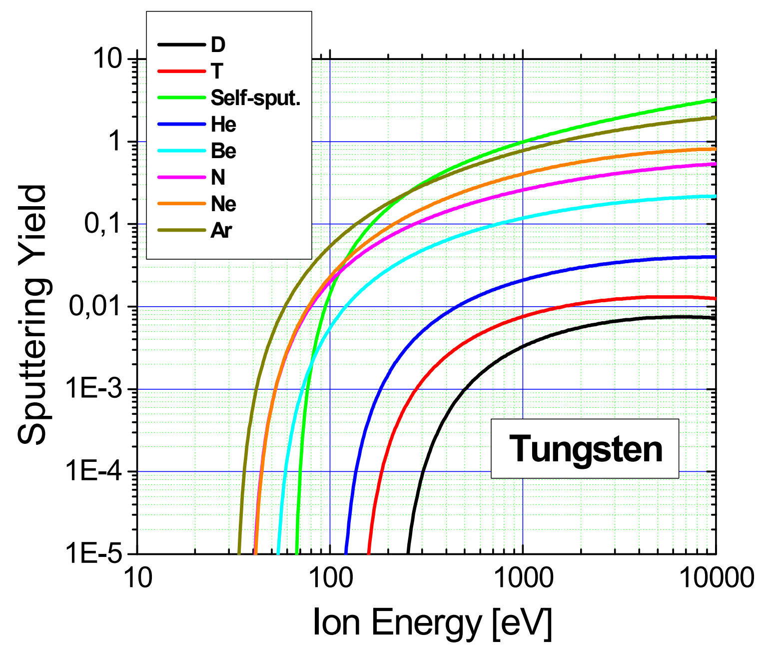
$$D_j^{an,k} = D_i^{an}$$

SOL Model



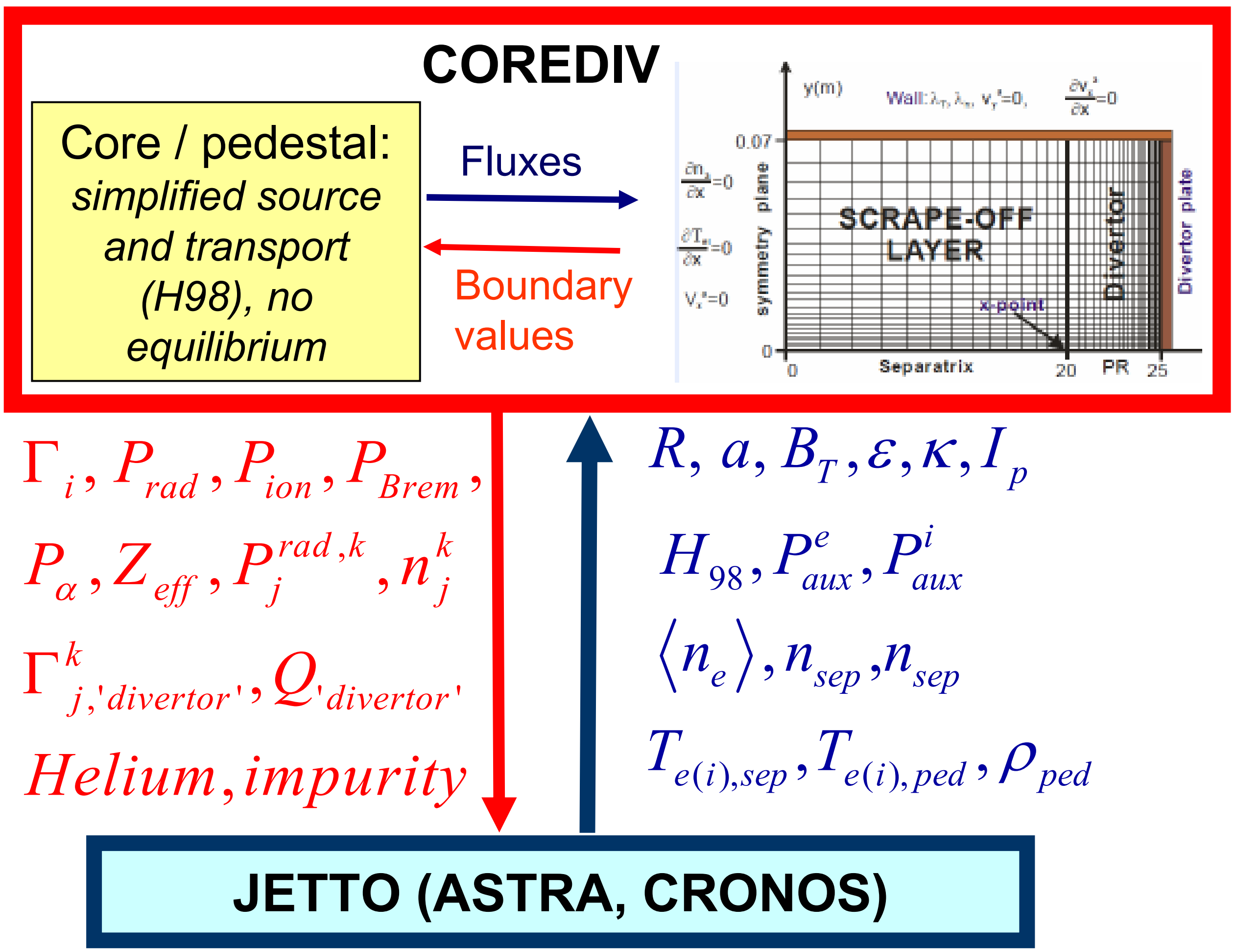
- **Slab geometry** (lack of PR), drifts neglected
- **Atomic processes**: ionization, recombination, excitation, charge exchange
- **Analytical model for neutrals** accounts for plasma recycling and impurity sputtering (also by seeded impurities). Recycling is an external parameter
- **Boundary conditions**: sheath, decay lengths; input fluxes from core part of the model
- **Intrinsic and seeded impurities** – gas puff at different positions

- 2D multifluid transport based on **Braginskii equations**
- Particle balance, parallel momentum, two energy equations
- Transport: parallel - classical, radial –anomalous



He, Li, Be, B, C, N, O, Ne, Si, Ar, Ti, Ni, Mo, W

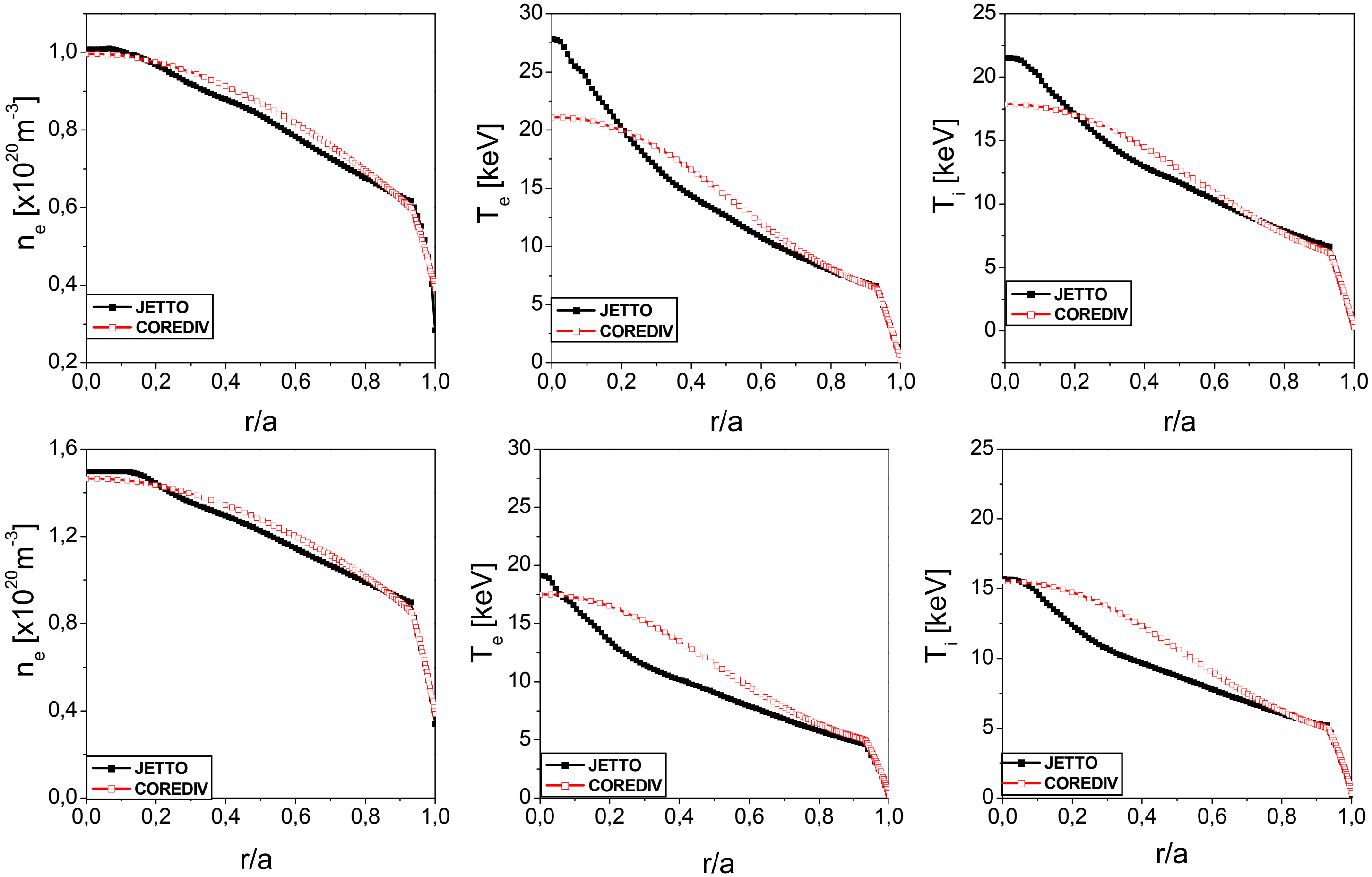
Coupled JETTO-COREDIV simulations for H-mode ITER plasmas



- ITER H-mode scenario: 15 MA, 5.34 T, 33 MW (NBI) + 20 MW (ECRH)
- JETTO / GLF23 (H98=0.85) with EPED and SOLPS boundary
- Low density:
  n_{e_ped}=6e19 m^{-3}
  $T_{e,ped}$ = 6.7 keV
  $T_{i,ped}$ = 7.5 keV
- High density:
  n_{e_ped}=9.5e19 m^{-3}
  $T_{e,ped}$ = 4.35keV
  $T_{i,ped}$ = 4.83keV

In ITER simulations we use the same version of COREDIV, which is used for JET!

Profile of n_e, T_e and T_i



low density

high density

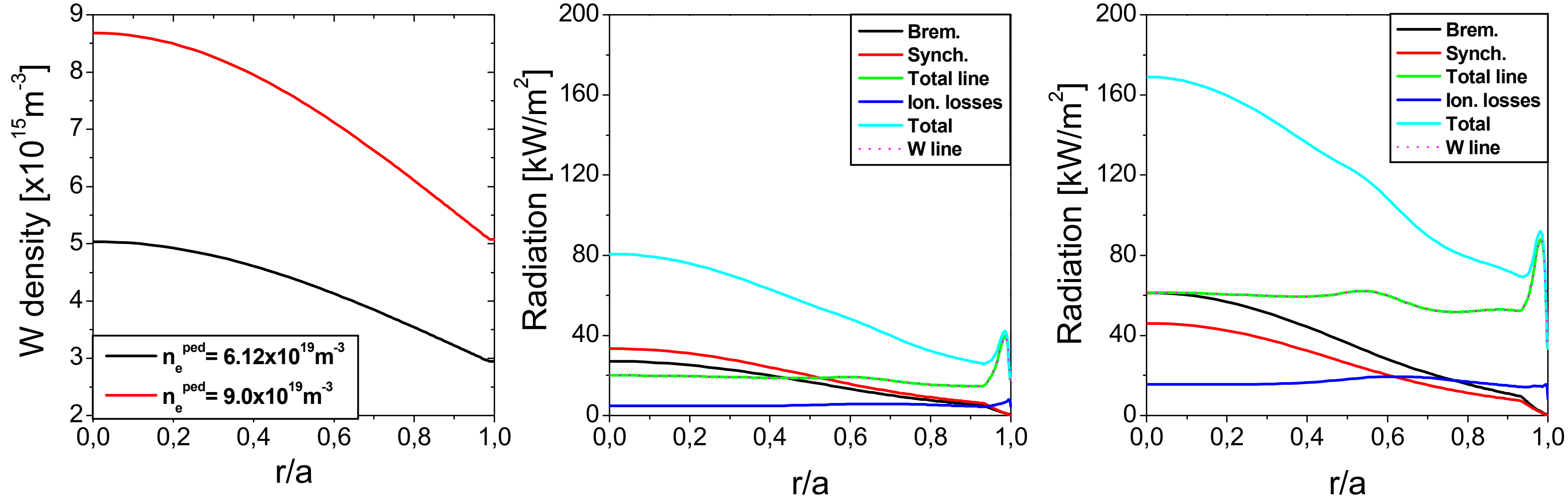
Comparision with JET simulation:

- high peaking of the density profile (4 times larger V_{pinch} than for JET plasmas)
- smaller edge barrier (for JET, b = 0.15, for ITER b = 0.11)

Profile of the tungsten density, radiation for two cases ($V_{pinch}^{IMP}=V_{pinch}^{MAIN\ PLASMA}$, without Ne seeding)

Case 1: low density

Case 2: high density



Parameters	Case 1	Case 2
P_{α} [MW]	79.4	140.1
P_{SYNCH} [MW]	11.67	15.1
P_{LIN} [MW]	19.92	42.52
P_{BREM} [MW]	9.71	19.98
P_{SOL} [MW]	83.65	80.4
P_{CORE} [MW]	41.92	89.97
Radiation Fraction	0.378	0.505
Total heating [MW]	133	193

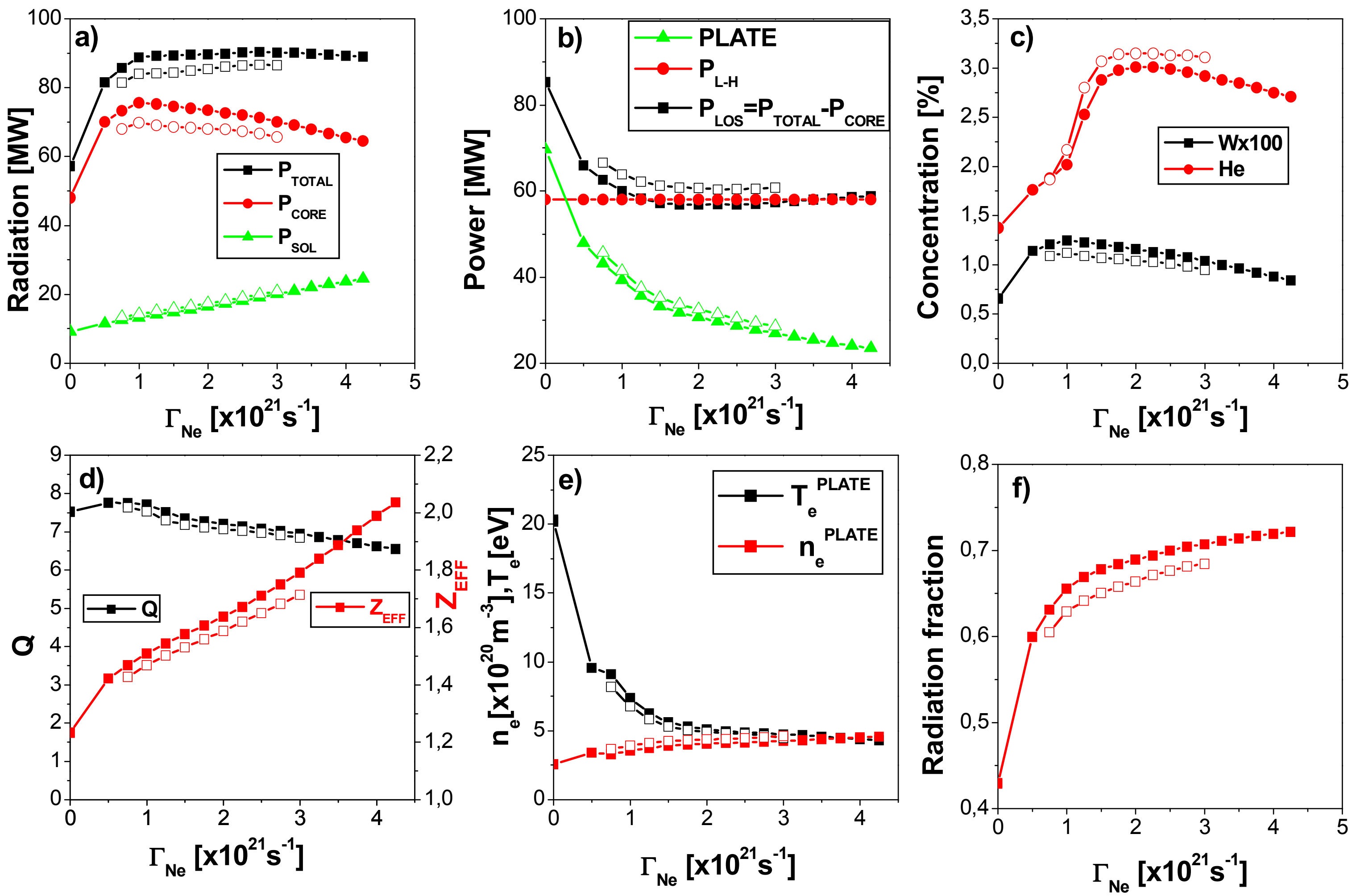
Power to Plate[MW]	**76.05**	**85.32**
T_e^{PLATE} [eV]	25.45	33.55
n_e^{PLATE} [$x10^{20}m^{-3}$]	2.1	1.43
Recycling coefficient	0.9958	0.989

Power to plate is not acceptable for operation window for ITER divertor (10 MW/m²).

ITER needs gas puffing!

Sputtering	**Case 1**	**Case 2**
D	3.17	4.42
W(self-sputtering)	7.806	14.505
He	0.781	0.502

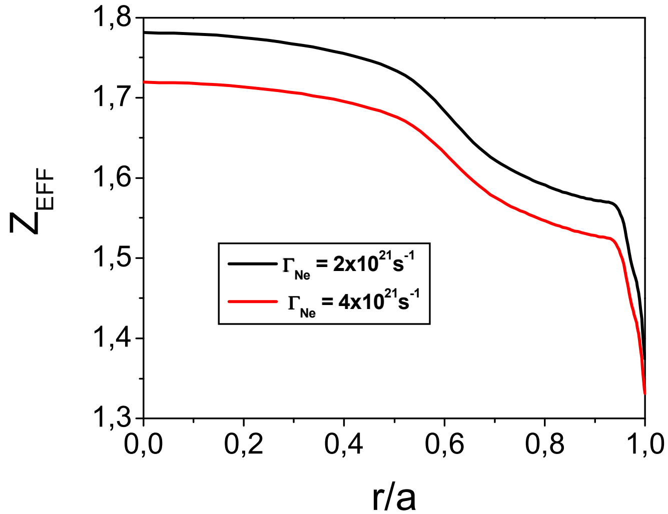
Ne gas puff for two different density on the separatrix

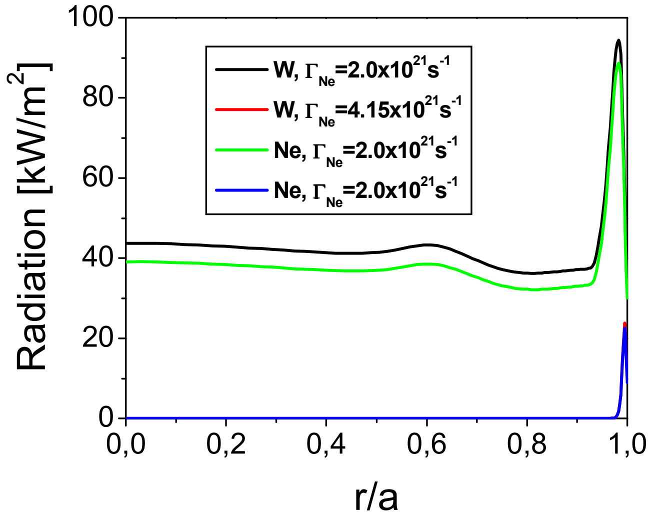


n_{sep}=3.25x10^{19} m^{-3} (full symbols)
n_{sep}=3.5x10^{19} m^{-3} (open symbols)

The effect of separatrix density on the power through the sepatarix is weak!

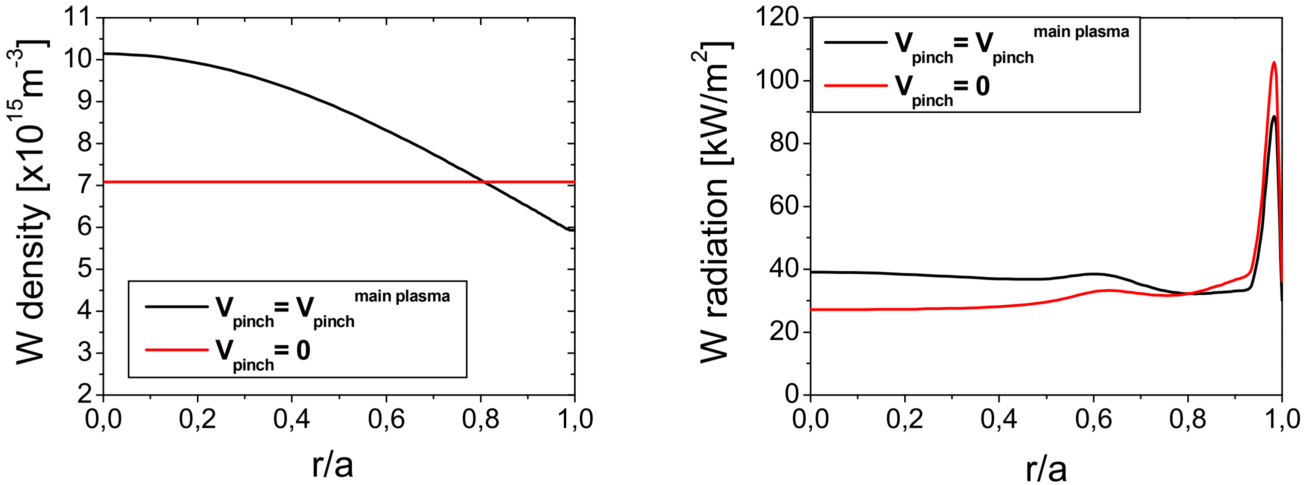
Influence on the Ne gas puff to the profile on the Z_{EFF} and radiation





Tungsten density nW (left) and Ne radiation (right) with Γ_{Ne} = 2x10^{21} and 4.15x10^{21} part/s

Effect on the V_{pinch}^{IMP}



Tungsten density and radiation obtained in simulations
with $V_W = V_D$ (black) and $V_W = 0$ (red) with $\Gamma_{Ne} = 2x10^{21}$ part/s

- for zero W inward pinch $V_W = 0$ the W concentration reduces only by 8.5%
- core radiation reduces only by 2.4 MW

CONCLUSION

Taking into account two essential constraints:

- ❖ H-mode operation (i.e. $P_{loss} > P_{LH}$)
- ❖ low divertor heat loads (power to divertor does not exceed 40 MW)
  - Ne seeding is essential for reducing the power to plate below 40 MW
  - W sputtering by Ne is important, it replaces the W self-sputtering leading to a larger W accumulation and core radiation, than in the case without Ne seeding
  - H-mode operational point with power to plate slightly below 40 MW is barely above the L-H power threshold in regimes with Ne seeding due to large W radiation. The H-mode operation is sensitive to the separatrix density and W inward pinch.

It should be mentioned that the strong coupling between the W accumulation (or transport) and radiation, reducing the power to plate, divertor temperature and W production, which in its turn affects the W accumulation leads to a “stiff” operational point and make it difficult to estimate in advance the trend with engineering parameters. More extensive parameter scans are needed to determine if the operational space for robust H-mode ITER performance with high fusion yield and acceptable level of divertor heat loads exist.