On the performances of future tokamak devices based on scaling law predictions

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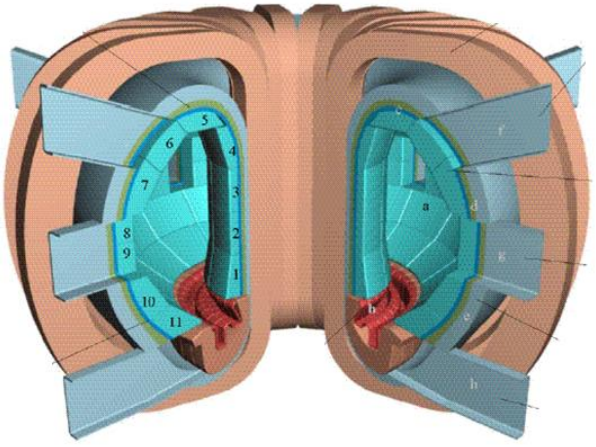
Towards a fusion power plant

Tokamak experiments and theoretical research have indicated the direction to demonstrate and pursuit the scientific validity and exploitation of fusion energy

- ☐ Sizable electrical output ⇒ large plasma volume or strong toroidal magnetic field
- ☐ Longer pulse ⇒ optimization of the plasma shape and magnets
- ☐ Minimize risks ⇒ operational margin from limits (n_{GW}, β-limits...)

On this principles is based the extrapolation to future devices

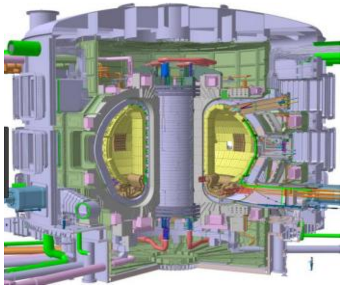
Machines such as ITER and DEMO will represent a transition between the physical experiments and the fusion power plants



Zohm H. NF(2013)
Federici NF(2017)
Siccinio NF(2018)

DEMO demonstration fusion power plant

ITER

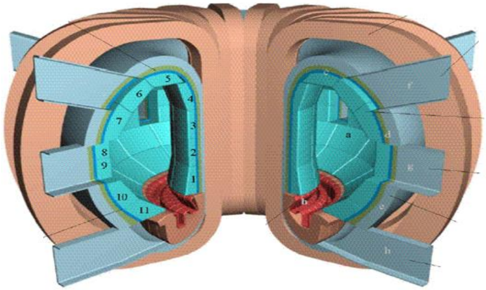


P_{fus}=500 MW Q=P_{fus}/P_{aux}=10 β_N=1.8 n/n_{Gw}=0.85

H-mode plasmas are the reference operating scenario in ITER.

- Problems of ELMs

DEMO



P_{fus}=2 GW Q≈40 β_N=3 n/n_{Gw}≈1.0

It is planned that also DEMO will operate in H-mode

- Problems linked to ELMs could be serious

The current state of physical knowledge and technological limits does not yet well allow us to identify the best combination of solutions to decide the architecture of this new tokamak

Overview

- ☐ The parametric dependence of transport is essential to optimize future devices
  On the basis of the transport model we can have a variation of H_f and consequently of P_{fus}

- ☐ An important element of tokamak research finalized to the prediction, the interpretation and the planning of experiments is represented by the *'integrated modeling'*

- ☐ The integrated modeling tool ASTRA+TGLF is used in order to investigate scenarios of interest for DEMO. We obtain scaling laws which describe and serve as a guide-line for the pre-conceptual design of the machine

- ☐ We investigate the performances of the reactor in terms of

  - ➢ fusion power,
  - ➢ confinement time quality *H-factor*
  - ➢ fusion power multiplication factor Q

in different regimes

- ❖ *H-mode*
- ❖ *ELM-free regimes (I-mode, L-mode)*

ASTRA –TGLF simulations

ASTRA *is a highly flexible transport tool dedicated to integrated simulations. It is very popular in the fusion community*

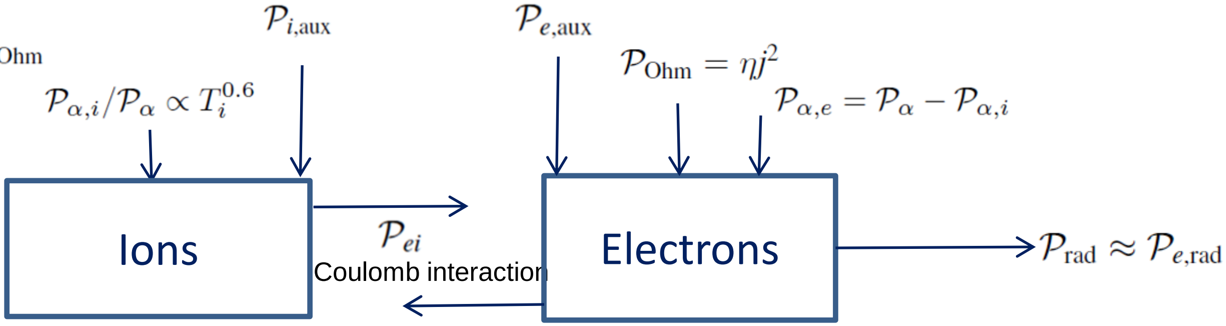
The basic set of equations in the ASTRA code includes expressions for n_e, T_e, T_i *and the poloidal flux*
The schematic structure of ASTRA assumes a transport matrix that connects the sources and the flux of energy

Power density sources

$$\mathcal{P}_e = \mathcal{P}_{\alpha,e} - \mathcal{P}_{ei} + \mathcal{P}_{e,\text{aux}} - \mathcal{P}_{e,\text{rad}} + \mathcal{P}_{\text{Ohm}}$$

$$\mathcal{P}_i = \mathcal{P}_{\alpha,i} + \mathcal{P}_{ei} + \mathcal{P}_{i,\text{aux}}$$

$$\mathcal{P}_\alpha = f_{\text{coup}} \mathcal{P}_{\text{fus}}$$



Pereverzev IPP Rep5/42 (1999)
Fable NF(2013)

TGLF *is a code based on first principles with a more comprehensive physics than the models previously developed*

Validation in reactor relevant scenarios

DIIID	*Kinsey NF (2008)*
ASDEX Upgrade	*Fable NF(2019)*
JET	*Baiocchi NF(2015)*
C-mod	*Creely NF(2017)*

Large amount of simulations for a variety of plasma elongation, triangularity, high β value

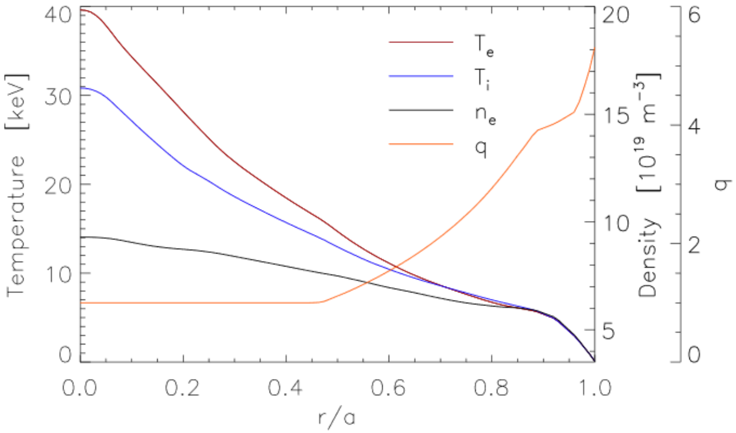
Significant progress made on *L- and H-mode.* Recently, the attention moves also towards regimes such as the *I-mode*

Stabler POP(2005)

Nominal case (baseline 2018)

Parameters	Values
Major radius	$R = 9.01$ m
Minor radius	$a = 2.9$ m
Aspect ratio	$A = R/a = 3.1$
Nominal toroidal field	$B = 5.8$ T
Elongation	$\kappa = 1.7$
Triangularity	$\delta = 0.35$
plasma current	$I_p = 17.75$ MA

Equilibrium profiles



$$P_{\text{aux}} = 48.2 \text{ MW}$$

$$P_{\text{rad}} = 133.5 \text{ MW}$$

$$q_{95} \approx 4$$

D-T plasma with 8.7% *He* fraction

The final balance of Helium quantity depends on the transport and on the external conditions like pumping

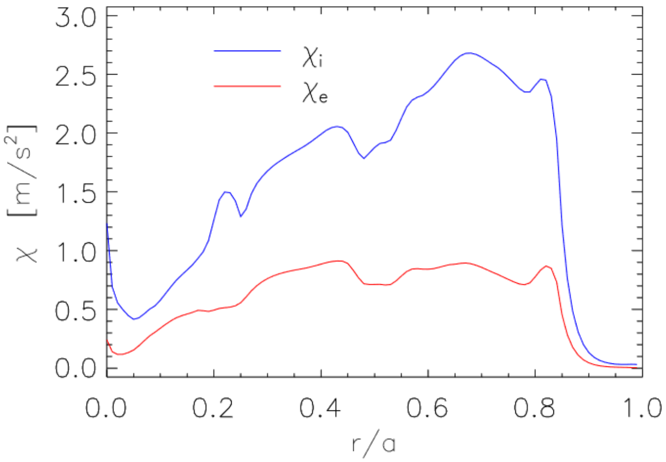
$$\rho_* = \rho_L / a \approx 10^{-3}$$

at mid-radius

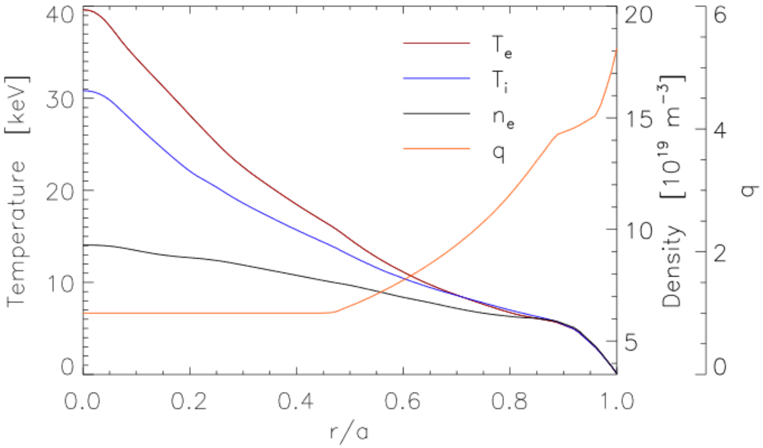
The small value of ρ_* implies that the global effects are negligible and this justifies the local approach adopted in the model

Heating flux estimation and assumption on *q*

Ion and electron heat conductivity



Equilibrium profiles



$$Q_i = -n_i \chi_i \nabla T_i > Q_e = -n_e \chi_e \nabla T_e$$

The principal instability in the simulations is related to the ITG

Common characteristic for all our scans and therefore for the different regimes (*H-, I- and L-mode) investigated in the work*

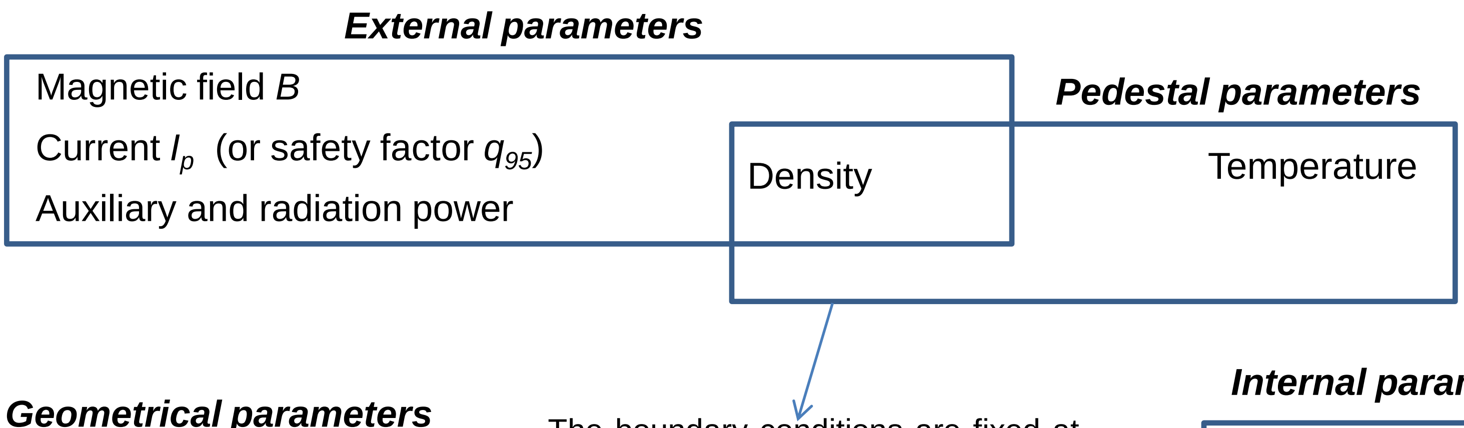
The effects of sawteeth on the core for temperature and density profiles are not taken into account

However, a flat safety factor profile in the core has been considered as if a sawtooth activity is always present

This is because, the less optimistic situation from the point of view of the confinement has been described

Rationale of the work

Performed scans on different parameters in order to investigate relevant regimes for DEMO



External parameters

Magnetic field *B*

Current I_p (or safety factor q_{95})

Auxiliary and radiation power

Pedestal parameters

Density

Temperature

Geometrical parameters

Major radius *R*

Aspect ratio *A*

The boundary conditions are fixed at the pedestal top.
The top temperature is a free parameter, in this way the regression allows to explore various regimes in a coherent manner

Internal parameters

Safety factor q_{core}

ExB

Helium concentration

The closure of this model is obtained by selecting the conditions at the pedestal for example by considering a pressure model (EPED or I-mode...)

When a pedestal model is considered, the stored energy is predicted and the *H-factor* becomes an output value

⇒

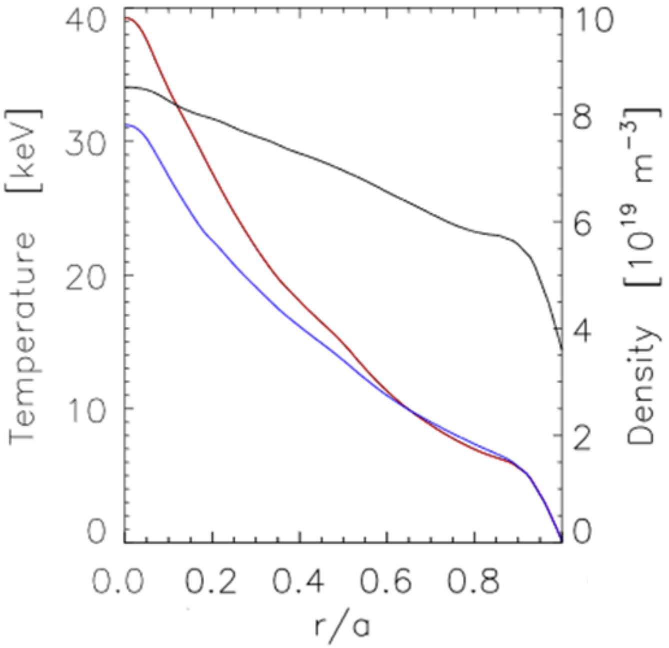
⇐

If a pedestal model is not given, an assumed *H-factor* value as input gives indications about the pedestal pressure

Scan in T_p and n_p

The most critical region that must be predicted/described is the edge pedestal

Modeled pedestal temperature and density



Pedestal top $r/a \approx 0.92$

Pedestal width $\Delta r \approx 23$ cm

Reference values

$T_p = 5.5$ keV The temperature value for the nominal case is consistent with the EPED stability calculation (*Saarelma NF (2018*)

$$n_{Gw} = \frac{I_p}{\pi a^2} \longrightarrow n_{Gw} = 6.2 \cdot 10^{19} \text{ m}^{-3}$$

$$3.5 \text{ keV} \leq T_p \leq 6.2 \text{ keV}$$

$$0.8\, n_{Gw} \leq n_p \leq 0.9\, n_{Gw}$$

Due to several constraints, density is a parameter more critical than temperature

Greenwald limit never exceeded

Scan in P_{aux} and P_{rad}

Impurities are considered for dilution and P_{rad} is scanned independently
The effect of radiation on the temperature is the dominant effect

$$\mathcal{P}_{\text{rad}} \approx \mathcal{P}_{e,\text{rad}}$$

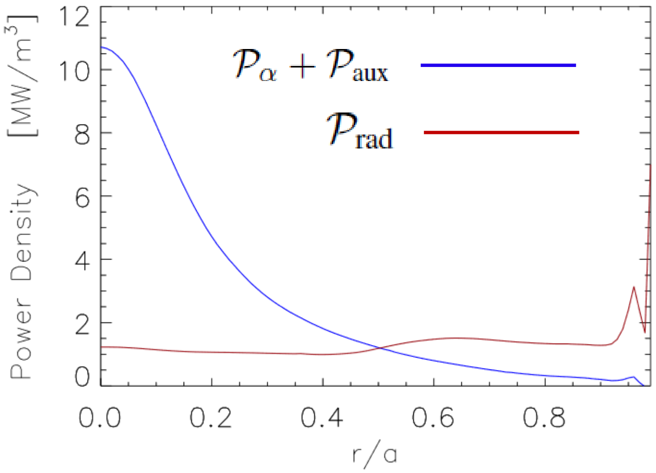
- ✓bremsstrahlung of electrons on ions
- ✓electron synchrotron radiation that becomes important at high temperatures
- ✓Radiation effects of Xenon and Argon enter as an additional contribution in the radiation power

$$\mathcal{P}_{\text{aux}} = \mathcal{P}_{e,\text{aux}} + \mathcal{P}_{i,\text{aux}} \qquad \mathcal{P}_{e,\text{aux}} = \mathcal{P}_{i,\text{aux}}$$

Distributed in equal amount

P_{rad} concerns principally the edge region

$P_{\text{aux}} + P_{\alpha}$ involves the central region of tokamak



$$0 \text{ MW} \leqslant P_{\text{aux}} \leqslant 100 \text{ MW}$$

$$30 \text{ MW} \leqslant P_{\text{rad}} \leqslant 235 \text{ MW}$$

Scan in R, B, I_p, A

Parameters involved in several physical and technological problems

Ex:

❑$I_{p,max}$ depends on many different factors:

✓Coils break point (engineering problem)

✓Generation of unstable kink modes that lead to a strong and fast deformation of the plasma boundary and the plasma disruptions (physical problem)

$$q_{ed} = \frac{2\pi}{\mu_0} \frac{RB}{I_p A^2}$$

Relation that involves all the scan parameters for a circular poloidal shape

$$q_{ed} \geqslant 3$$

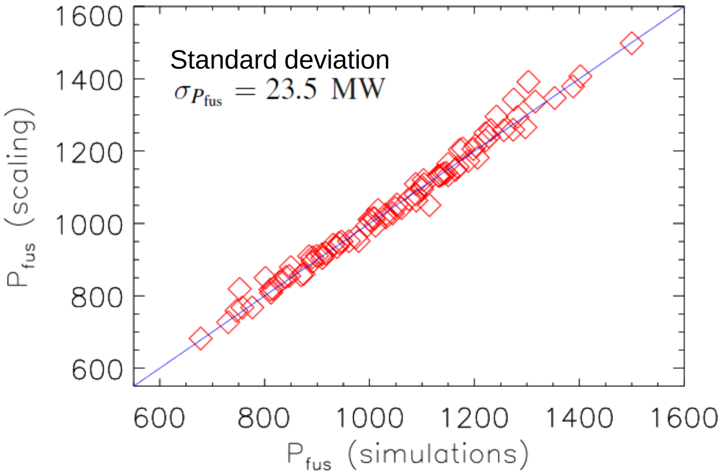
Stable regimes require sufficiently high q_{ed} values related to the maximum current

$$8.5\ \mathrm{m} \leqslant R \leqslant 9\ \mathrm{m} \qquad 5.8\ \mathrm{T} \leqslant B \leqslant 6.2\ \mathrm{T}$$

$$16\ \mathrm{MA} \leqslant I_\mathrm{p} \leqslant 19\ \mathrm{MA} \qquad 2.9 \leqslant A \leqslant 3.1$$

Scaling law and physical interpretation

By considering all the performed simulations, we obtain the following robust regression for P_{fus}:



The scaling law has been obtained by considering that also in the case in which ***P_{aux}*** and ***P_{rad}*** are equal to zero, the ***P_{fus}*** must be different from zero

P_{rad} is concentrated at the edge of tokamak where we impose boundary conditions. Therefore, ***P_{rad}*** cannot strongly influence the simulation results and in particular the physics of the core

$$P_{fus} = 0.053\left(\frac{n_p}{n_{Gw}}\right)^{2.29} T_{p,e}^{0.94} R^{-0.73} B^{1.23} e^{0.004(P_{aux}-0.2P_{rad})} I_p^{2.4} A^{1.08}$$

Reduction of the temperature dependence of the cross section with increasing temperature in the range between *30* keV and *40* keV.
The profile stiffness becomes stronger whit the increase of the temperature

The inverse dependence of the major radius reflects the fact that by increasing *R*, n_{GW} decreases and thereby at constant Greenwald fraction the density has to decrease at fixed current

Palermo NF (2019)

Scaling: engineering and physical point of view

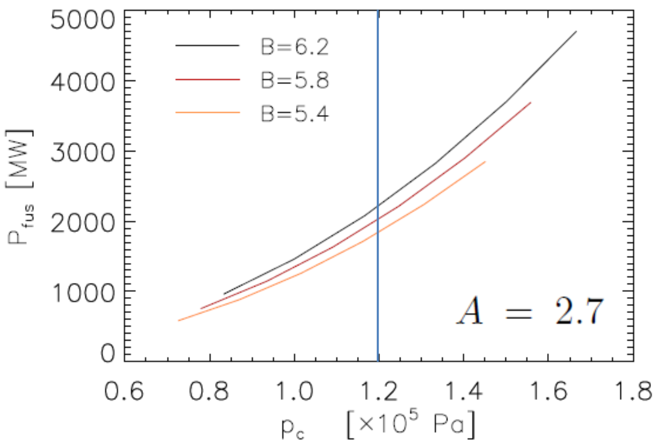
The most performing plasma configuration may not be compatible with the different technological and physical limits

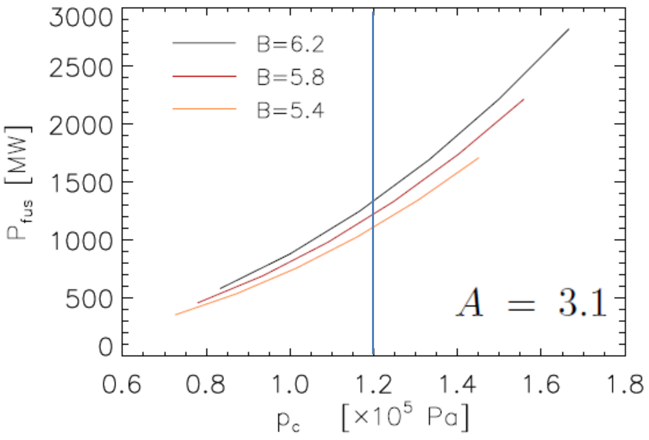
I_p replaced by q

$$P_{fus} = 6.5\left(\frac{n_p}{n_{Gw}}\right)^{1.35} p_{c,e}^{0.94} q^{-1.46} R^{2.61} A^{-3.7} B^{2.69} e^{0.004(P_{aux}-0.2P_{rad})}$$

By increasing *R,* for a fixed *q* value, I_p increases, n_{GW} decreases and consequently the n_p decreases, but in lower extent with respect to the previous case

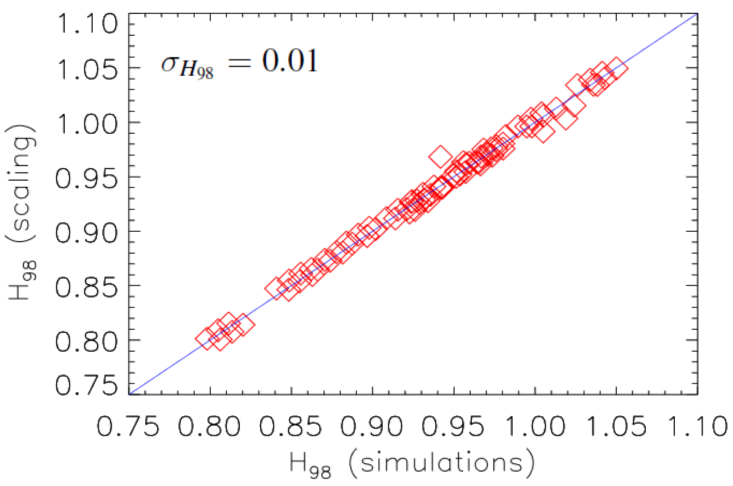
Sensitive dependence of the fusion power from the aspect ratio





$R = 8.5\ \mathrm{m}$ $\quad$ $q_{95} \approx 3.5$ $\quad$ $T_p = 6\,\mathrm{keV}$ $\quad$ $0.5 \leq n_p/n_{Gw} \leq 1$

Scaling law for the *H-factor*



Association of the *H-factor values* to the corresponding fusion power *values*

$$H_{98} = \frac{\tau_E}{\tau_E^{IPB98}}$$

$$\left(f_{coup} + \frac{1}{Q}\right) P_{fus} = \frac{W_t}{\tau_E}$$

$$\tau_E^{IPB98} = 0.0562 I^{0.93} B^{0.15} n^{0.41} P^{-0.69} M^{0.19} R^{1.97} A^{-0.58} \kappa_a^{0.78}$$

$$H_{98} = 0.33\left(\frac{n_p}{n_{Gw}}\right)^{-0.13} p_{c,e}^{0.49} R^{-0.27} B^{-1.21} e^{-0.0003(P_\alpha+P_{aux}+P_{rad})} q^{1.30} A^{1.41}$$

By using the nominal values of several machines, H_{98} equation allows us to obtain the expected *H-factor value for* devices such as ARC and ITER

This scaling law cannot obtain the correct *H-factor value* of ASDEX Upgrade and smaller machines. This is principally due to dependence of P_{fus} *—and consequently of* P_α*— on the* size of the machines

Essentially, the scaling law cannot be applied to devices having zero or too small values of P_{fus}

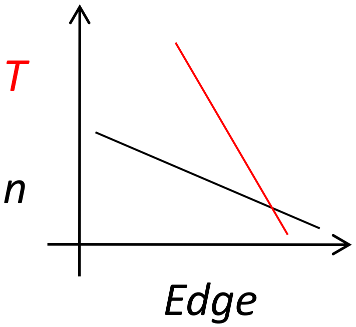
Pedestal conditions in several regimes

In order to establish a regime in which we can avoid the problem of ELMs, it is important to identify the pressure conditions in which ELM free regimes (*I-mode) exist*

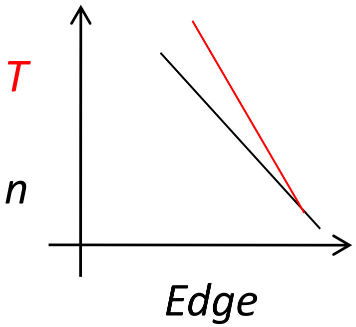
	L-mode	I-mode	H-mode
$\eta_i = \frac{d \ln T_i}{d \ln n} = \frac{L_n}{L_T}$	$\approx 2.5–8$	$\approx 2.5 - 5$	$\approx 0.5–1$

Table with indicative values of ratio between temperature and density gradient for different considered regimes

$$\eta_I \approx 5\eta_H$$



Ryter PPCF(1998)



Wagner PRL(1984)

White NF(2010)
Palermo EPL(2016)

H-mode and I-mode in DEMO

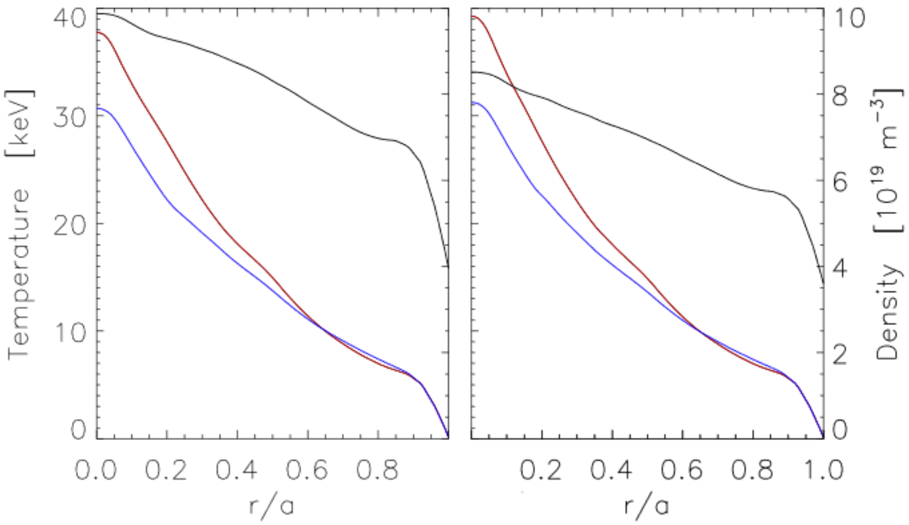
We model the pedestal profile of temperature and density with the following expressions:

$$T = \frac{1}{2}\left[2T_p - \Delta T\left(1 + \tanh\left(\frac{x - x_1}{l_T}\right)\right)\right]$$

$$n = \frac{1}{2}\left[2n_p - \Delta n\left(1 + \tanh\left(\frac{x - x_1}{l_n}\right)\right)\right]$$

$$0.90 \lesssim x \lesssim 1 \qquad\qquad x = r/a$$

$$n_{Gw} = 8.18 \cdot 10^{19}\ \mathrm{m}^{-3}$$



H-mode

$T_p = 5.5keV$

$n_p = 0.9\, n_{Gw}$

$r/a = 0.92$

$\eta_H \approx 3.3$

$x_1 = 0.95$

I-mode

$T_p = 5.5keV$

$n_p \approx 0.75 n_{Gw}$

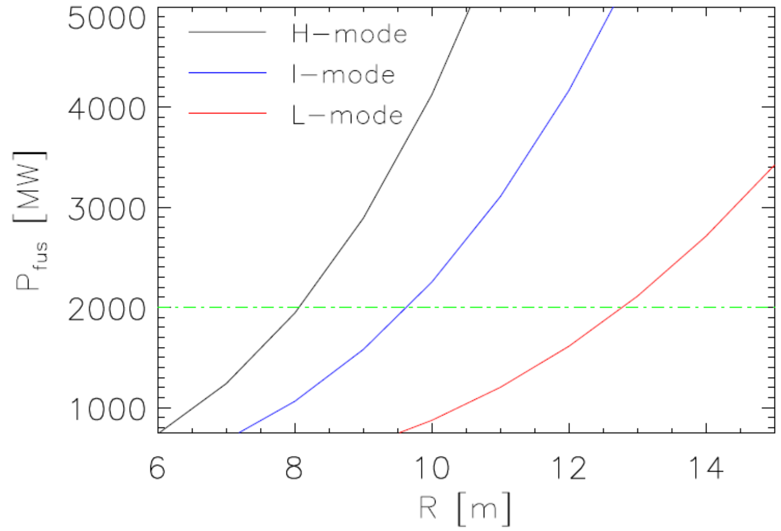
$r/a = 0.92$

$p_{c,e} \approx 0.54 \cdot 10^5 Pa$

$\eta_I \approx 4\eta_H \approx 13.2.$

$x_1 = 0.95$

Fusion power in H-mode, I-mode, L-mode



$$q_{95} = 3.5 \qquad A = 3 \qquad B = 6\ \mathrm{T}$$

$$P_{aux} = 50\ \mathrm{MW} \qquad P_{rad} = 200\ \mathrm{MW}$$

$$P_{fus}/5 + P_{aux} - P_{rad} > 0$$

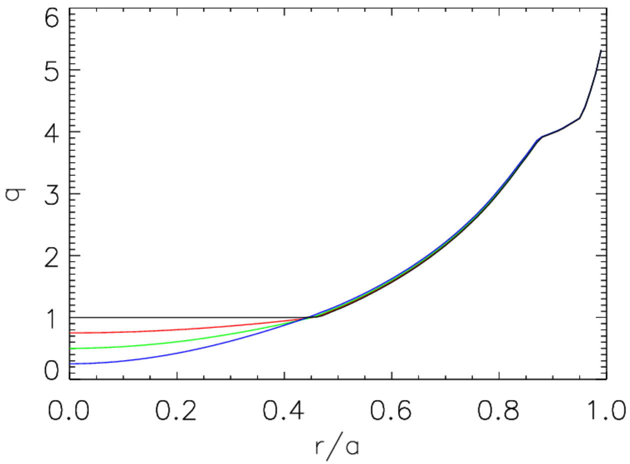
$$P_{fus} > 750\ \mathrm{MW}$$

$$R = 8.5\ \mathrm{m}$$

Regime	n_p/n_{Gw}	P_{fus} (MW)	Q	H_{98}
H-mode	0.90	2300	46	0.9
I-mode	0.75	1400	28	0.8
~~*L*-mode~~	~~0.75~~	~~400.0~~	~~8~~	~~0.5~~

Extension of the work: internal parameters

This work can be extended in several directions. For example the influence of internal parameters can be taken into account



Internal parameters

Safety factor in the core, ExB, Helium concentration

Ex: Safety factor q_c

Transport is large for large safety factor in the core *(q_0=1)* and decreases by decreasing the q_0 value

$$P_{fus} \propto \left(\frac{n_p}{n_{Gw}}\right)^{1.35} p_{c,e}^{0.94} q^{-1.46} R^{2.61} A^{-3.7} B^{2.69} e^{0.004(P_{aux}-0.2P_{rad})} q_0^{-0.24}$$

Theoretical explanation:

Low q_0 values favour the stability of the ITG modes and the development of the zonal flow

Experimental evidence:

This trend has been observed in DIIID: scenarios without sawtooth events showed that the safety factor goes down and the confinement strongly increases

Palermo et al. in prepar. (2019)

Conclusions

☐ We used the *ASTRA* code and the TGLF model to deduce scaling laws to investigate the characteristics of scenarios for future tokamak reactors. Starting from a nominal case, we performed scans in:

Geometrical parameters *External parameters* *Pedestal parameters*

☐ We have found a very robust regression which allows us to optimize the plasma scenario and which can be easily coupled to different codes (ex: Process)

☐ We have shown that it is possible to move towards regimes such as I-mode, that avoid the problem of ELMs, obtaining at the same time very good performance for DEMO in terms of P_{fus}, *H-factor* and Q