Impurities in a Reactor

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Overview

- Introduction
  - Impurities in Fusion Plasmas

- Impurity limits
  - Simple 0D and 0.5D approach
  - 1D ASTRA model

- What Physics Issues Need to be Addressed?
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Impurity Sources
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- Erosion from first wall
  (e.g. W, Be, C.....)
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- Production of He in reactor core

\[ ^2_1 D + ^3_1 T \rightarrow ^4_2 He + ^1_1 n \]

\[ 3.5\text{MeV} \quad 14.1\text{MeV} \]
Impurity Sources

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- Production of He in reactor core

\[
\begin{align*}
\frac{2}{1}D + \frac{3}{1}T & \rightarrow \frac{4}{2}He + \frac{1}{1}n \\
3.5\text{MeV} & \ 14.1\text{MeV}
\end{align*}
\]

- Intentionally injected impurities (e.g. N, Ne, Ar, Kr...)
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- What Physics Issues Need to be Addressed?
$$A) \text{ Power balance: } \quad P_\alpha = P_{rad} + P_{transp}$$

$$P_\alpha = \frac{n_e^2}{4} \langle \sigma u \rangle E_\alpha (1 - 2c_{He} - Z_i c_i)^2$$

$$P_{rad} = n_e^2 \left( (1 - 2c_{He} - Z_i c_i)L_H + c_{He} L_{He} + c_i L_i \right)$$

$$P_{transp} = \frac{3kTn_e}{2\tau_E} (2 - c_{He} - (Z_i - 1)c_i)$$

$$\Rightarrow \quad n_e T \tau_E = f(T, c_{He}, c_i)$$

$$B) \text{ He balance: production = losses}$$

$$\frac{n_e^2}{4} \langle \sigma u \rangle (1 - 2c_{He} - Z_i c_i)^2 = \frac{n_e c_{He}}{\tau_{He}}$$

\[\text{define: } \rho^* = \frac{\tau_{He}}{\tau_E}\]

\[\Rightarrow \quad a_3(\rho^*, T, c_i)c_{He}^3 + a_2(\rho^*, T, c_i)c_{He}^2 + a_1(\rho^*, T, c_i)c_{He} + a_0(\rho^*, T, c_i) = 0\]
A) Power balance: \[ P_{\alpha} = P_{rad} + P_{transp} \]

\[
P_{\alpha} = \frac{n_e^2}{4} (\sigma u) E_{\alpha} (1 - 2c_{He} - Z_ic_i)^2
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\]

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\[
\Rightarrow n_eT\tau_E = f(T, c_{He}, c_i)
\]

- Fix \( \rho^*, T \) and \( c_i \)
- \( \leq 2 \) meaningful solutions for \( c_{He} \)

B) He balance: production = losses

\[
\frac{n_e^2}{4} (\sigma u) (1 - 2c_{He} - Z_ic_i)^2 = \frac{n_e c_{He}}{\tau_{He}}
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define: \( \rho^* = \frac{\tau_{He}}{\tau_E} \)

A+B \[ a_3(\rho^*, T, c_i)c_{He}^3 + a_2(\rho^*, T, c_i)c_{He}^2 + a_1(\rho^*, T, c_i)c_{He} + a_0(\rho^*, T, c_i) = 0 \]
0D-Model - Simple Power Balance

\[ P_\alpha = P_{rad} + P_{transp} \]

- For fixed \( \rho^* \) and variation of \( c_{Xe} \)
  => plots with burn curves
- Burn curves become a single dot for maximum impurity level
- low-Z impurities decrease via dilution
- high-Z impurities increase

Pütterich, EPS 2015

Reiter, NF 1990
For fixed $\rho^*$ and variation of $c_{Xe}$ as
$\Rightarrow$ plots with burn curves

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\[ P_\alpha \]

\[ P_{rad} \]
W from wall, seeded impurities, He-ash
- W from wall, seeded impurities, He-ash
- W from wall, seeded impurities, He-ash
- Burn window becomes small
W from wall, seeded impurities, He-ash
Burn window becomes small

Is the situation changing for more realistic assumptions?
Implementation of T- and n-Profiles – Model Still Very General

Profiles of n,T vs. r/a using circular plasma

Any Plasma may be mapped onto a circular one

Approximation: Linear Profiles, Flat Impurity Concentration

Parametrized via peaking $R_T = T_0/<T>$, $R_n = n_0/<n>$

Results are size independent

For $\rho^*<5$ small effect (<20%)

Pütterich, EPS 2015 – now improved model
Implementation of finite Q also Possible

\[ Q = \frac{P_{fus}}{P_{aux}} = \frac{5P_\alpha}{P_{aux}} \]

- Q > 30 economically viable
- Finite Q can be seen as an artificially increased \( P_{\alpha,eff} \)
  \[ P_{\alpha,eff} = P_\alpha + P_{aux} = \frac{Q+5}{Q} P_\alpha \]
- Note: Fixed Synchrotron radiation can be taken into account, but depends on \( B_t \) & \( R \)

=> Talk today by E. Fable

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\[ \rho^* = \frac{\tau_{He}}{\tau_E} \]

\(\rho^* = 0, c_{Xe} = 0 \), \( c_{Xe} = X/2 \), \( c_{Xe} = X \)

EP DEMO1 2015

Pütterich, EPS 2015 – now improved model

\( T_0, 0.5D \) Models, \( R_t = 2.1, R_n = 1.3, Q = \infty, 40, 10 \)
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Pütterich, EPS 2015 – now improved model
Realistic Boundary Conditions also Define Reactor Design: Dilution, Radiative Fraction

- Strong Dilution of fuel makes a fusion power plant inefficient
- Radiative Fraction must be considerable to provide power exhaust

(Q, sync. rad. and profile peaking match EU DEMO1 2015)
Realistic Boundary Conditions also Define Reactor Design:

Dilution, Radiative Fraction

- Strong Dilution of fuel makes a fusion power plant inefficient
  => assume >71% D+T
- Radiative Fraction must be considerable to provide power exhaust
  => assume >50% radiative fraction

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  - 1D ASTRA model (fusion+radiation profile, transport, $Q < \infty$)

- What Physics Issues Need to be Addressed?
Why does radiation in a reactor not degrade confinement?

- Wall protection necessary
- ~500MW of alpha power
- Threshold in Turbulence Activity
  - Stiff gradients for power fluxes above threshold
  - Power flux may be reduced down to threshold, wo. confinement degradation

\[ \frac{\nabla T}{T} \]
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Reactor Core is more Vulnerable to Radiation

- Power flux at mid radius larger than in center
  - Volume vs. Surface for flux surface
    \[ V_{circ.} = 2\pi^2 R r^2 \]
    \[ S_{circ.} = 4\pi^2 R r \]
Reactor Core is more Vulnerable to Radiation

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  - Volume vs. Surface for flux surface
    \[ V_{\text{circ.}} = 2\pi^2 R r^2 \]
    \[ S_{\text{circ.}} = 4\pi^2 R r \]
- Seeded Impurities should radiate at the plasma edge
Core Radiation May Damage Temperature Profiles

- ASTRA simulations of a DEMO-like reactor
- T-profiles calculated using TGLF (Staebler PoP 2007)
- Localized radiative cooling
  - Core cooling damages T-profiles
  - Edge cooling with small impact

E. Fable NF 2017
Core Radiation May Damage Temperature Profiles

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- T-profiles calculated using TGLF

![Graph showing temperature profiles with Gaussian $P_{\text{rad}}(r)$, width = 0.1]
Are Xe, Kr and Ar better 'Mantle Radiators' than W?
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- In Reactor, the radiative mantle is between ~5keV and ~20keV

- What is the best radiator at the mantle for a certain ‘damage’ in the plasma core?
  - Ratio of core vs mantle radiation
  - W is slightly better than Xe, Kr and Ar!
  - Differences between radiators less than factor 2 (~uncertainties)
Are Xe, Kr and Ar better 'Mantle Radiators' than W?

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- Note: core impurity transport is easily as important
EU-DEMO1 design 2015 modelled with ASTRA

- Full 1D ASTRA model (Wenninger NF 2014)
- EU DEMO 2015 design (Wenninger NF 2017)
- Profiles of 50MW auxiliary heating and radiation
- \( P_{\text{fusion}} \) calculated => fusion yield \( Q = \frac{P_{\text{fusion}}}{P_{\text{aux.heating}}} \)
- Impurity seeding to obtain \( P_{\text{separatrix}} = 160 \text{MW} \)
- Heat & particle transport may be modelled, here: fixed density profiles, ad-hoc heat transport

<table>
<thead>
<tr>
<th>Parameter</th>
<th>EU DEMO1 2015</th>
</tr>
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<tbody>
<tr>
<td>( R [m] )</td>
<td>9.1</td>
</tr>
<tr>
<td>( A )</td>
<td>3.1</td>
</tr>
<tr>
<td>( B_T [T] )</td>
<td>5.7</td>
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<tr>
<td>( I_P [MA] )</td>
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</tr>
<tr>
<td>( H ) (rad. cor.)</td>
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<td>( \beta_{N,tot} [%] )</td>
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<td>( f_{bs} [%] )</td>
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<tr>
<td>( P_{\text{sep}}/R [MW/m] )</td>
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</tr>
<tr>
<td>( \tau_{\text{burn}} [h] )</td>
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</tr>
<tr>
<td>( P_{\text{fusion}} [MW] )</td>
<td>2037</td>
</tr>
<tr>
<td>( Q )</td>
<td>40</td>
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</tbody>
</table>
1D ASTRA: Operational Space Larger at Cost of Q

- Find Condition:
  Reduce power flux to $1.2^*P_{LH}$ at pedestal-top

- Steady-State operation possible for large

- But: Sacrifices in Q
  - Efficiency of power plant
  - Cost of electricity

\[ \rho^* = \frac{\tau_{He}}{\tau_E} \]
Find Condition: Reduce power flux to $1.2 \times P_{LH}$ at pedestal-top.

- Steady-State operation possible for large $Q$.

$$\rho^* = \frac{\tau_{He}}{\tau_E}$$

- But: Sacrifices in $Q$:
  - Efficiency of power plant
  - Cost of electricity

T. Pütterich, EFTC 2017, Athens - 37
1D ASTRA: Operational Space Larger at Cost of Q

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$\rho^* = \frac{\tau_{He}}{\tau_E}$

Small difference to 0.5D!
0.5D and 1D ASTRA Give Similar Answers

Pütterich, EPS 2015 - now improved model
What Physics Issues Need to be Addressed?

- Core radiation from Xe, Kr and Ar is as good/bad as from W
  ⇒ Impurity profiles should be preferably hollow (high-Z)

- How do the plasma profiles look in a reactor?
  ⇒ Realistic plasma transport

- Combine reactor performance (Q) with radiative cooling
  ⇒ Impurity profiles should be preferably hollow (low-Z)

  ⇒ Avoid divertor radiator in main plasma
    ⇒ divertor compression of N, Ne, Ar…
    ⇒ High-Z radiation (if tolerable) is preferable to low-Z dilution

  ⇒ Pump He well (divertor compression of He)
What Physics Issues Need to be Addressed?

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  true if turbulent transport dominant (Angioni NF 2017)

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  ⇒ Pump He well (divertor compression of He)
Divertor Compression Crucial

ASTRA + SOL model

- If low-Z radiators leak into main plasma, fusion losses may be large
- Surprising solution may be mid-Z radiator for divertor radiation
- Too few divertor compression of He-ash is a danger independently of solution for radiative cooling

Core radiator (here Xe) may have to be complemented by edge radiator

M. Siccinio, PPCF 2016