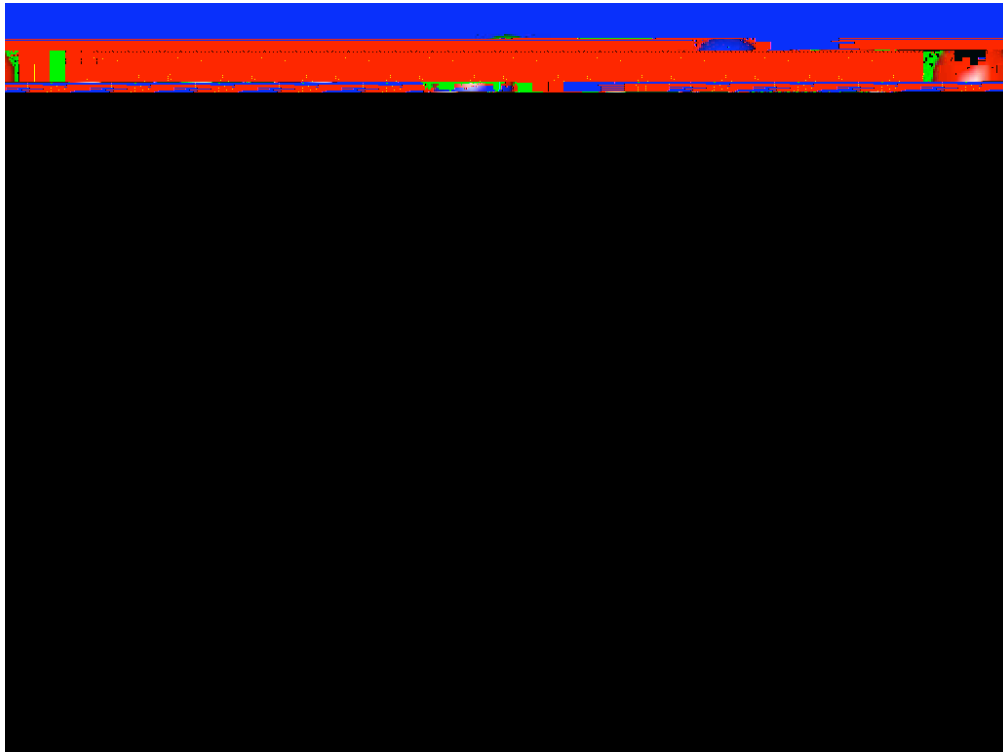
Outline

- Introduction
- Physical sputtering
- Chemical erosion
- Chemical sputtering
- Radiation enhanced sublimation
- Impact of impurities on fusion plasmas

Introduction

Physical sputtering

Molecular Dynamics simulation of 50eV He Be



Energetic particle impact involves a complex collision cascade during which:

- The projectile may be reflected back out of the surface
- The projectile may remain in the surface (=implantation)
- Surface atoms may be ejected out from the surface (= physical sputtering)
- The surface may be left with crystal damage.

Energetic particle impact is a stochastic process and is therefore described by giving average yields for the different processes

Physical sputtering

- Physical sputtering is the kinetic ejection of surface atoms by incident energetic ions or atoms due to collision processes.
- As surface atoms can escape only if it receives an energy larger than the surface binding energy, a threshold energy for the incident particles is required.
- In fusion application physical sputtering by hydrogen ions and atoms is important, but also the self-sputtering due to returning impurity atoms.

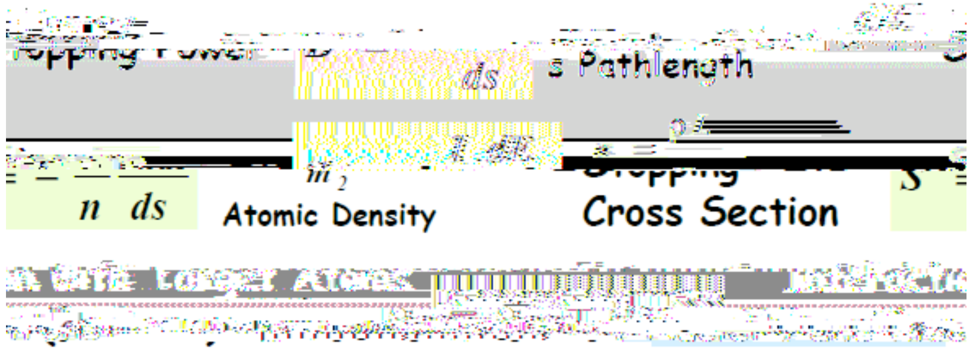
- TRIM Monte-Carlo Code simulation

Heavy ions:

- large collision cascade
- isotropic velocity distribution
- yield proportional to energy deposited in first 0004fy

Physical sputtering

stopping power



Stopping power is velocity dependent

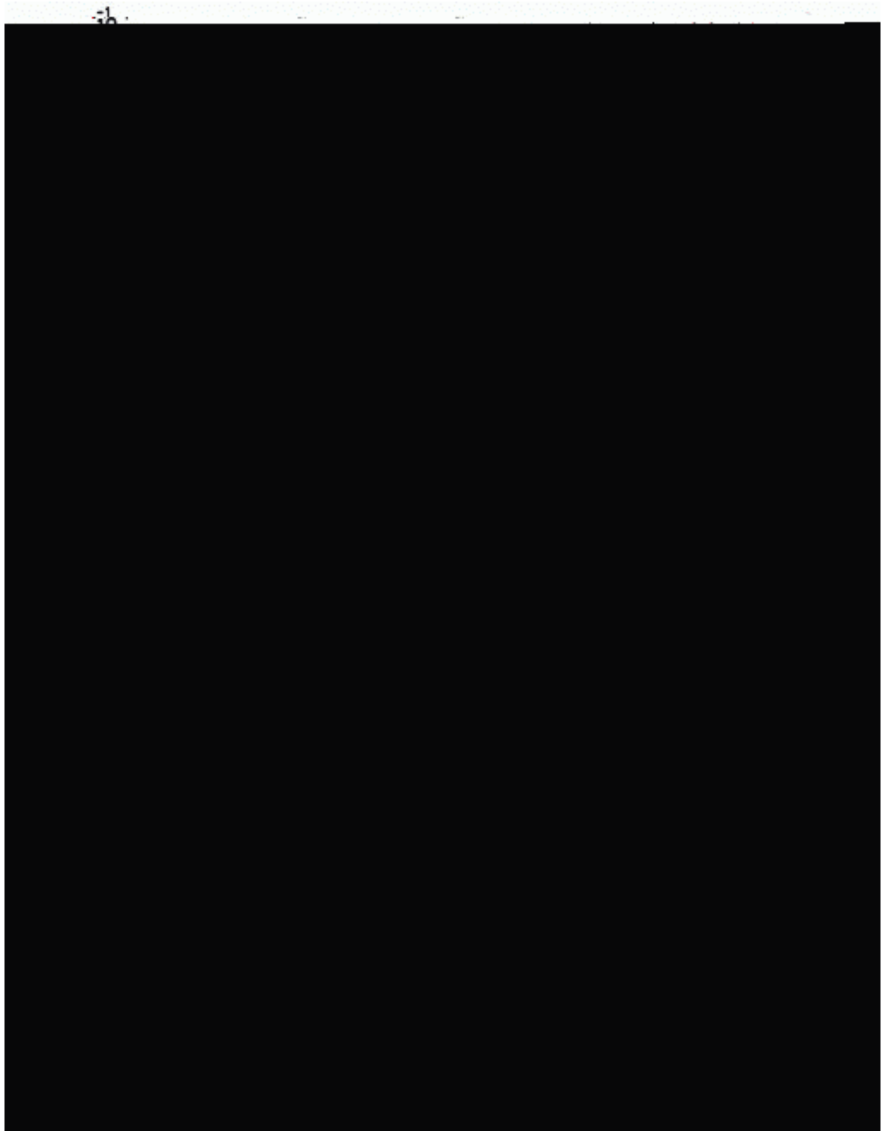
Fast particles stopping dominated by S_e

Slow particles stopping dominated by S_n

W. Möller PSE 2002 Tutorial

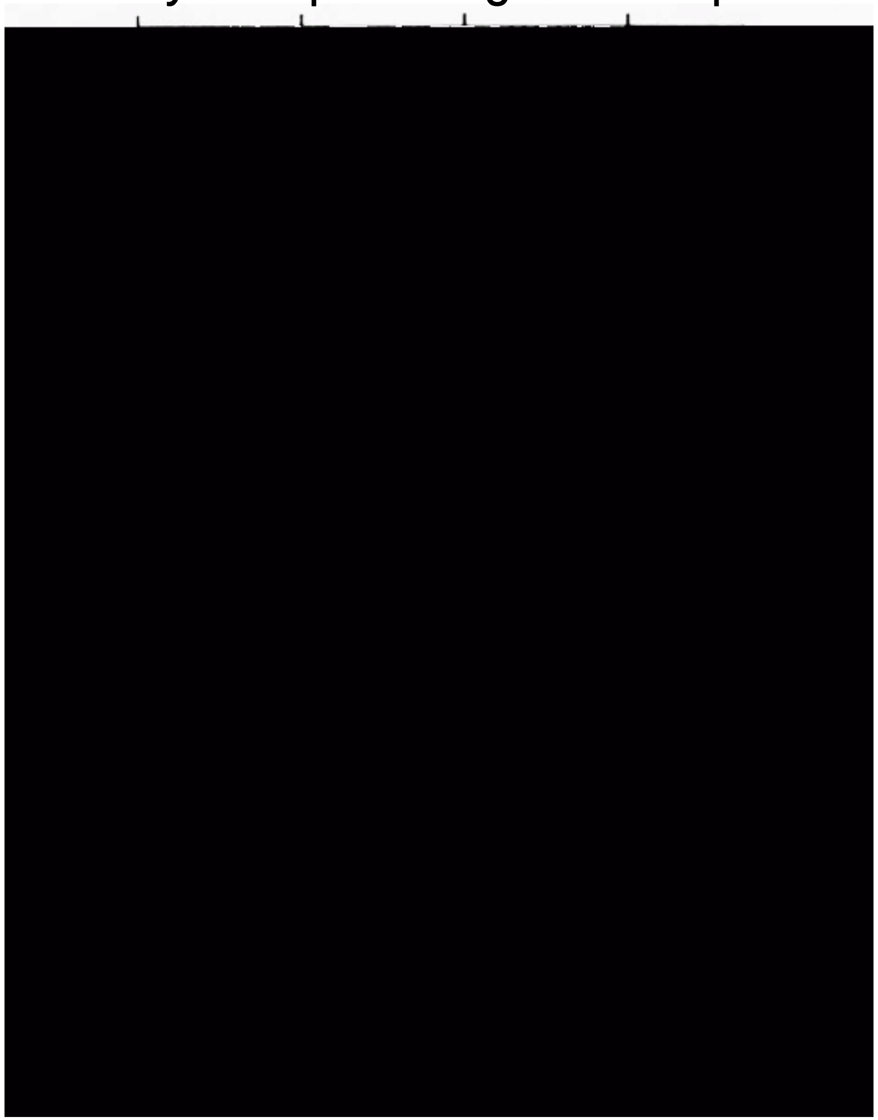
Physical sputtering

Threshold energy



- Light ion sputtering in fusion application is dominated by threshold effects

Theory for sputtering in isotropic collision cascades



Ansatz:
(P. Sigmund (1969))

Sputtering yield proportional to the energy deposited into collisions near the surface

$Y(\ ) \quad S_n(\ )_{x=0}/E_s$

$Y(\ ) = Q(M_1,M_2,E_S)*f_H(\ )$

E_s = Surface binding energy H heat of sublimation

physical sputtering

- Physical sputtering is the ***kinetic ejection of surface atoms*** by incident energetic ions or atoms ***due to collision processes***

  (playing pool with surface atoms).

- As surface atoms can escape only if it receives an energy larger than the ***surface binding energy***, a threshold energy for the incident particles is required.

- In fusion application sputtering by hydrogen and helium ions and atoms is important, but also the self-sputtering due to returning impurity atoms.

Chemical Erosion

- Chemical erosion originates from the formation and release of volatile molecules in the interaction of incident plasma particles and target atoms.
- In fusion application the formation of hydrocarbons in the interaction of hydrogen atoms with carbon surfaces is the dominant example of chemical erosion
-

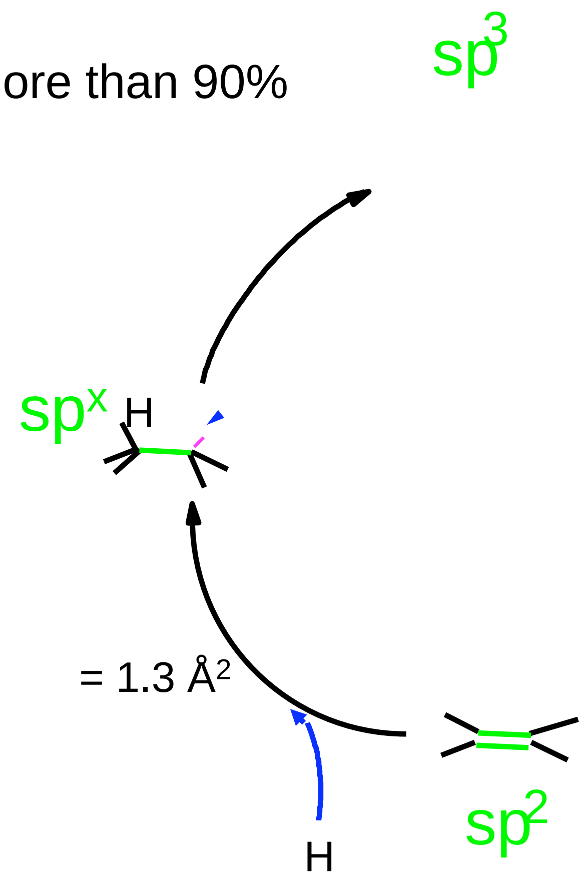
sp^2

Hydration and erosion circle:

Horn et al., Chem. Phys. Lett. 231, 193 (1994)

Zecho et alJ. Phys. Chem. B 105 (2001).

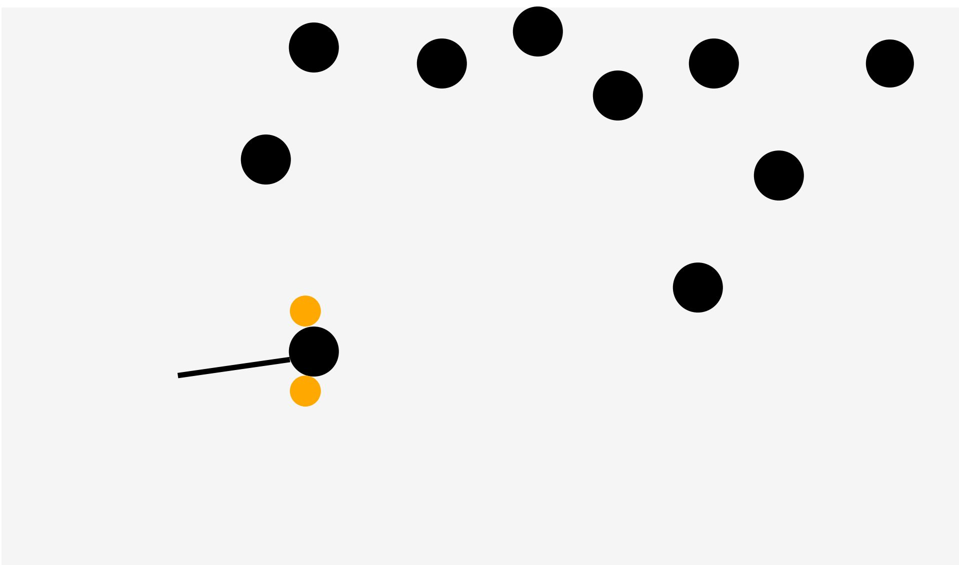
- hydration at room temperature of more than 90% of all possible adsorption sites
- erosion maximum as function of temperature



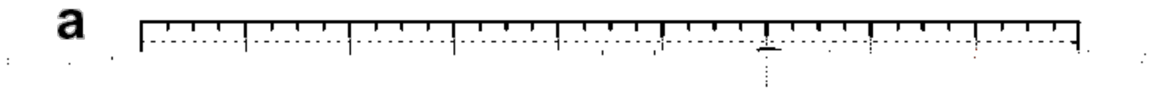
chemical erosion

- chemical erosion originates from the formation and release of volatile molecules in the interaction of incident plasma particles and target atoms.
- in fusion application the formation of hydrocarbons in the interaction of hydrogen atoms with carbon surfaces is the dominant example of chemical erosion.
- as chemical reactions are involved, chemical erosion shows a strong temperature dependence in contrast to physical sputtering.
- chemical erosion can occur with low-energy ions or thermal atoms and does not require a threshold energy.
- erosion will only take place at the very surface (1.4 nm pentration depth) or at the end of range of energetic particles.

it is not chemical erosion
H^0 at T > 400 K with a max. at



Temperature dependence

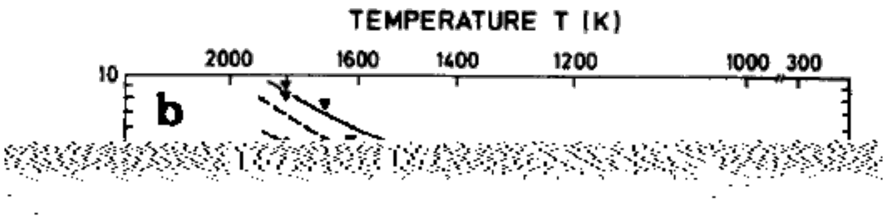


- Temperature dependence similar as for chemical erosion
- Radiation damage enhances chemical reactivity
- Value at T_{max} is larger than sum of chemical erosion and low temperature chemical sputtering

M. Schlüter, J. Nucl. Mater. 376, 33–37 (2008).

Radiation enhanced sublimation

Exponential fits yield activation energies



- Arrhenius activation energies are well below the graphite sublimation energy.
- Process occurs for both inert and reactive sputtering species
- Experiments indicate that eroded species have thermal energies

Radiation enhanced sublimation

- Diffusion trapping model quantitatively describes RES

- Damage profile calculated by TRIM.

- Under fusion conditions the influence of RES is not very pronounced:

  - At high fluxes the vacancy concentration becomes very high leading to fast annihilation of the more mobile interstitials.

  - For low particle energies close to the damage threshold no Frenkel pairs are created.

Radiation enhanced sublimation

- At high temperatures graphite exhibits an exponential increase in the erosion rate during energetic particle impact that can not be explained by sublimation

- A model using the sublimation of weakly bonded surface defects, quantitatively describe the process.

- Similar effects are also seen for metallic targets at very high fluxes and temperatures. more relevant for fusion.

Impact of impurities on fusion plasmas

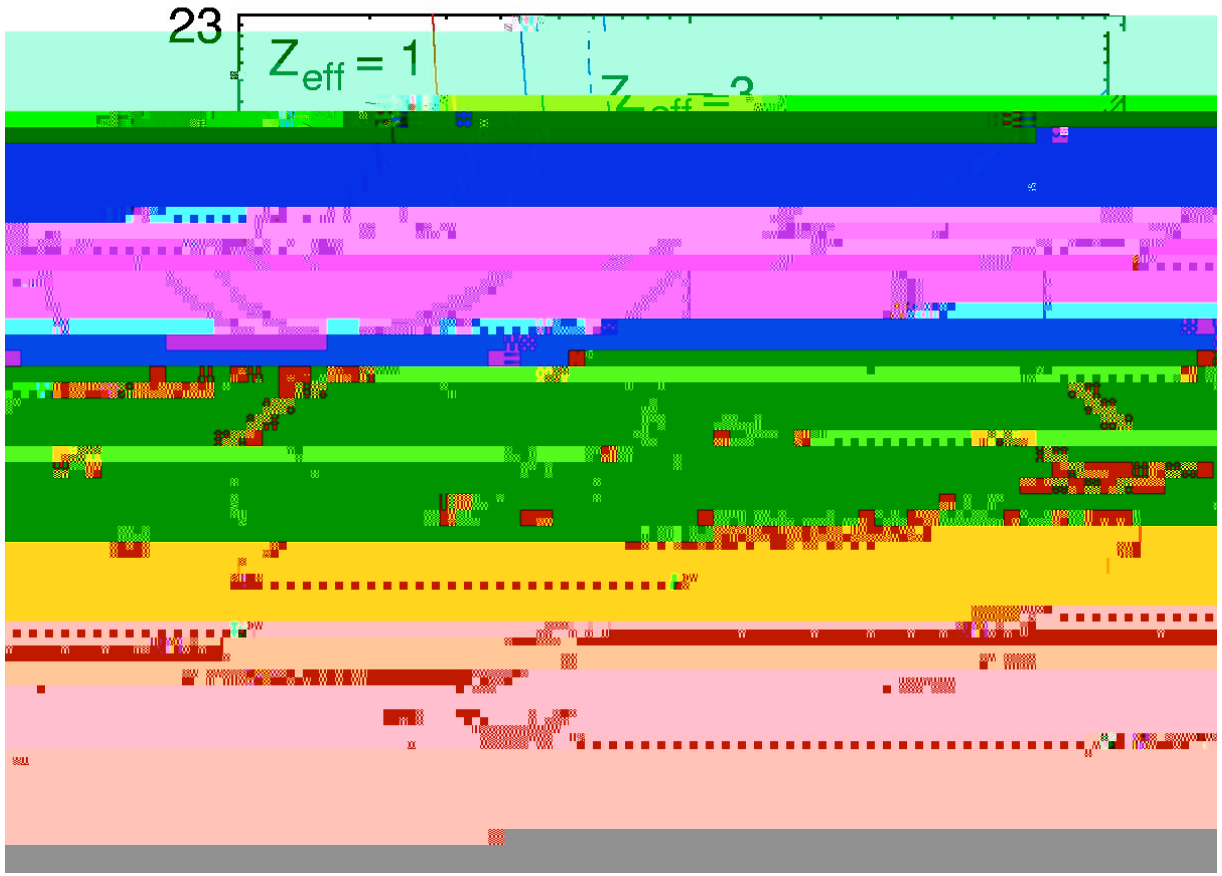
- As atoms are eroded from the first wall they enter the plasma
- In the plasma they are ionized and transported throughout the machine.
- What how does that affect the plasma ?

Impact of impurities on fusion plasmas

Impact of impurities on fusion plasmas

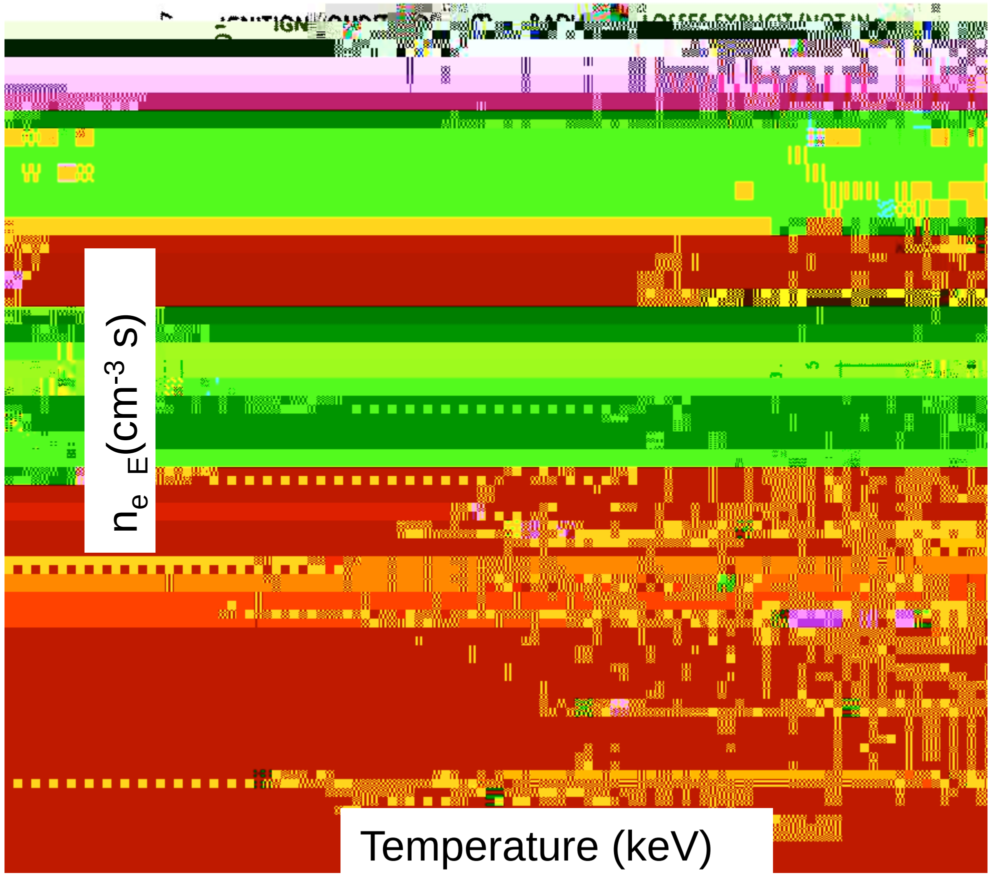
Ignition Criteria

- Ignition: The neutrons leave the plasma, the -particles are confined and heat it. Only their energy should enter the balance! E_{fus} E



K. Schmid 2009

- The -particles also dilute the plasma, as they are intrinsically coupled to fusion power (3.53•10

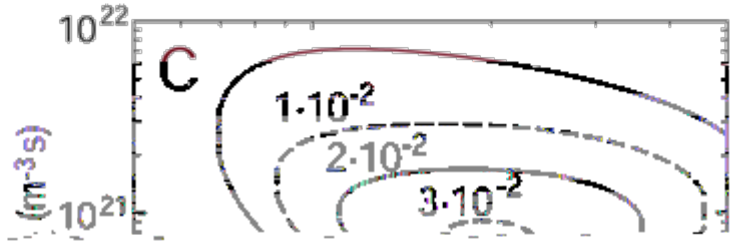


Impact of impurities on fusion plasmas

- Other impurities have a similar impact as He
    - Dilution of fuel ions

P_R

Ignition condition



→ No ignition for core W conc. > 10^{-4}

Impact of impurities on fusion plasmas

- As atoms are eroded from the first wall they enter the plasma
- In the plasma they are ionized and transported throughout the machine.
- In the plasma they radiate energy through line radiation and Bremsstrahlung.
- They also dilute the plasma.
- The radiative loss of energy from the plasma and its dilution through these impurities has fundamental implications for the operation of a fusion reactor!
- The erosion of wall components poses a lifetime problem
- The co-deposition of impurities (mainly C) with fuel ions poses a radiation hazard