Plasma-Surface Interactions

Effects of impurities in Tokamak

- Radiative power loss : line radiation
- Fuel dilution
- Radiation barrier : difficult to heat plasmas initially
- Disruptions : via edge cooling

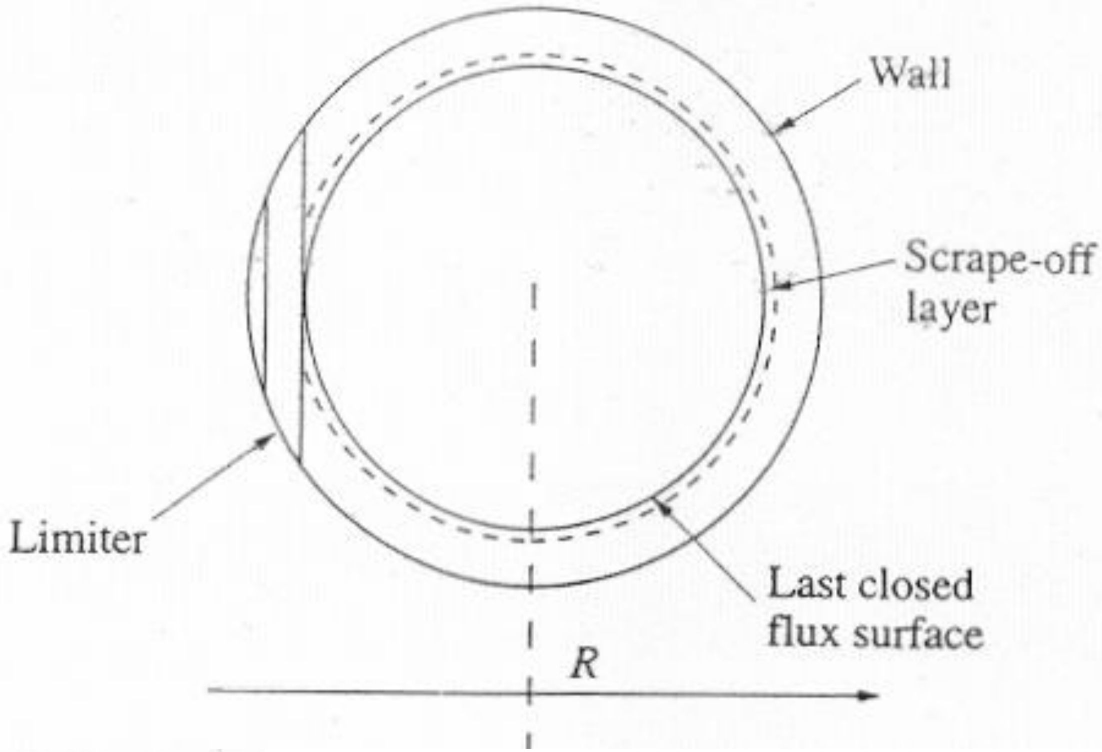
Sheath phenomena in Tokamak

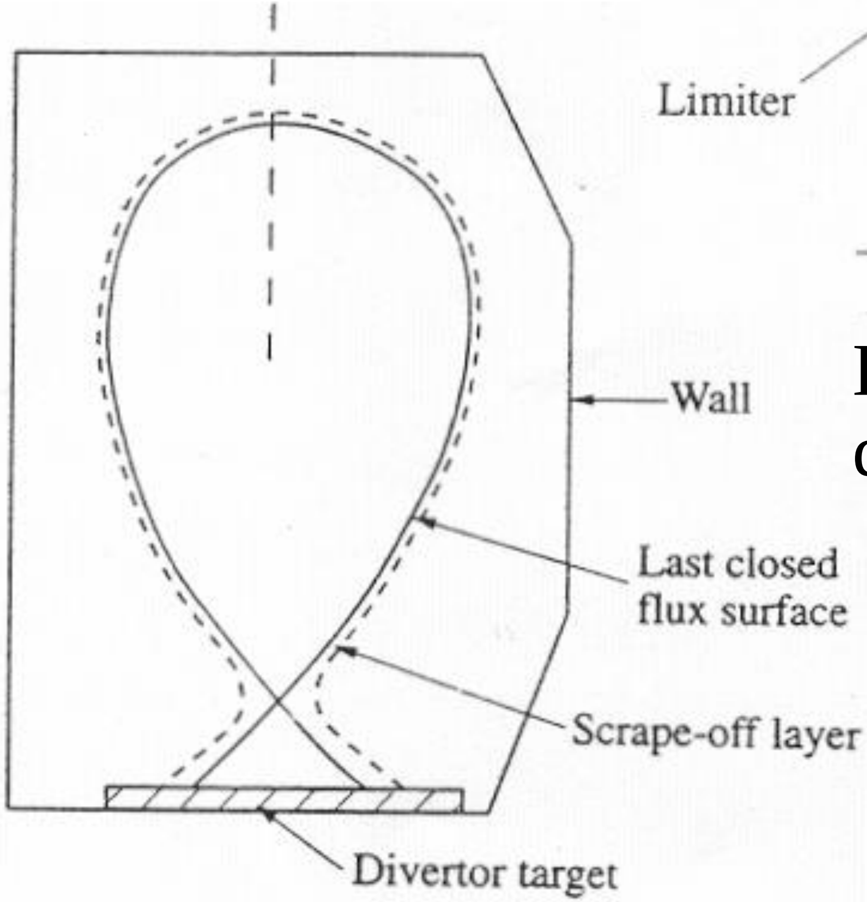
- Plasma sheath
- Scrape-off layer

Impurity-related processes

- Recycling
- Atomic and molecular processes
- Desorption : Wall conditioning
- Sputtering
- Arcing
- Evaporation

Plasma-Surface Interactions





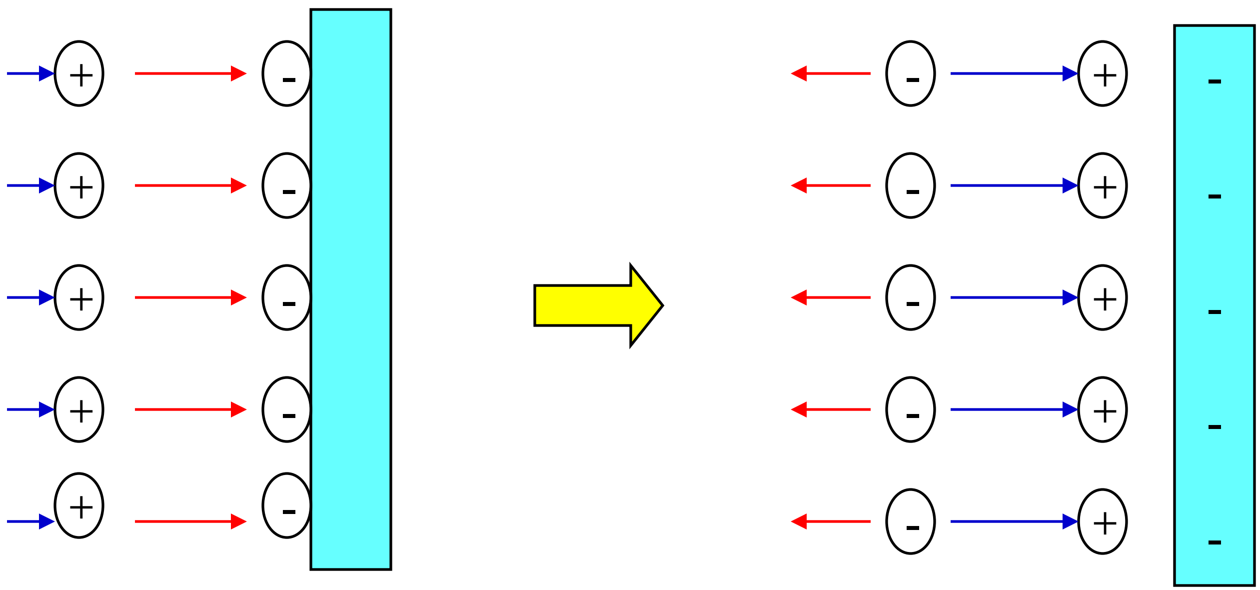
Last Closed Flux Surface(LCFS) determined by

- Limiters
- Divertors

Tritium Behavior

Basic Concepts of Plasma Sheaths : sheath formation

• Plasma sheath：the non-neutral potential region between the plasma and the wall caused by the balanced flow of particles with different mobility such as electrons and ions.

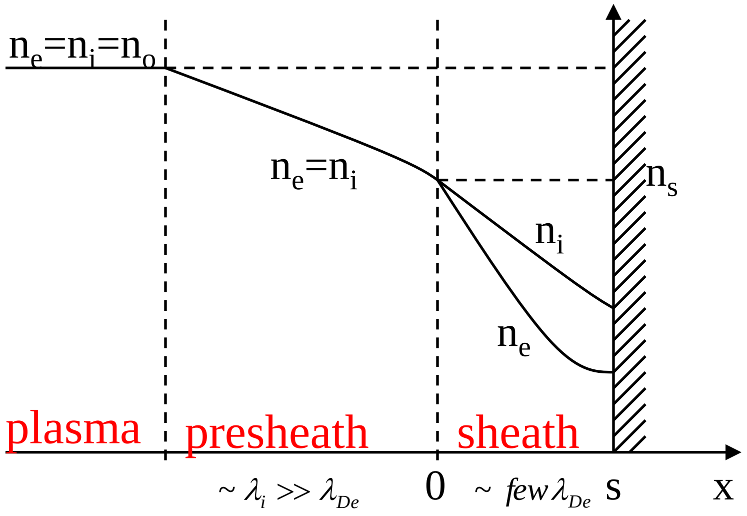


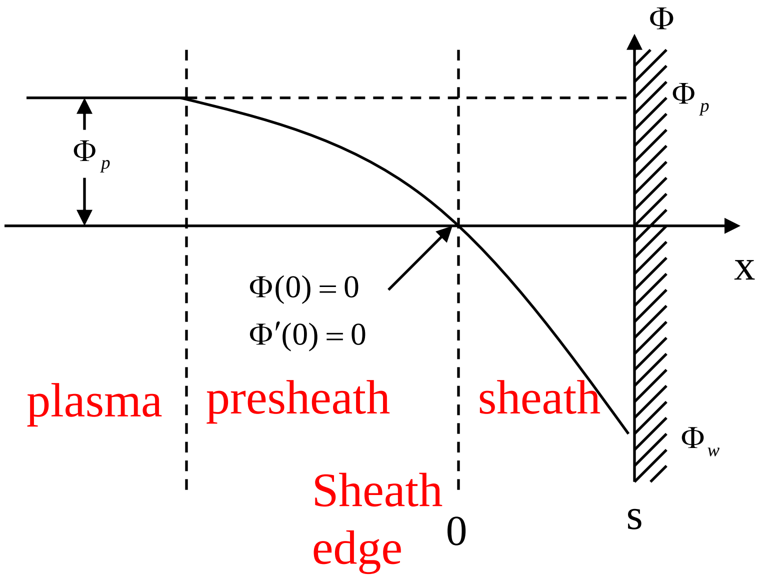
High electron mobility
--> negative potential buildup

• High energy ion bombardment
• Electrons are retarded
• **Ambipolar diffusion** established

Basic Concepts of Plasma Sheaths : presheath formation

• Presheath : a transition layer between the neutral plasma and the non-neutral sheath in order to maintain the continuity of ion flux, giving rise to an ion velocity at the plasma-sheath edge known as the Bohm velocity u_B.





Bohm Sheath Criterion

Electron density in Boltzmann distribution $$n_e = n_o \exp(e\Phi / T_e)$$

Ions entering into the sheath with velocity v_o $$\frac{1}{2} m_i v_i^2 = \frac{1}{2} m_i v_o^2 - e\Phi$$

Ion density in the sheath from constant ion flux

$$n_i v_i = n_o v_o$$

$$n_i = n_o \left(\frac{m_i v_o^2 / 2}{m_i v_o^2 / 2 - e\Phi} \right)^{1/2}$$

Electric potential at sheath by Poisson's equation $$\frac{d^2\Phi}{dx^2} = \frac{e}{\varepsilon_o}(n_e - n_i)$$

$$\frac{d^2\Phi}{dx^2} = \frac{n_o e}{\varepsilon_o}\left[\exp(e\Phi / T_e) - \left(\frac{m_i v_o^2 / 2}{m_i v_o^2 / 2 - e\Phi} \right)^{1/2} \right]$$

$$\frac{1}{2}\left(\frac{d\Phi}{dx} \right)^2 = \frac{n_o e}{\varepsilon_o}\left[T_e \exp(e\Phi / T_e) - T_e + m_i v_o^2 \left(1 + \frac{e\Phi}{m_i v_o^2 / 2} \right)^{1/2} - m_i v_o^2 \right]$$

$$\approx \frac{n_o e}{\varepsilon_o}\left[\frac{1}{2}\frac{(e\Phi)^2}{T_e} - \frac{1}{4}\frac{(e\Phi)^2}{m_i v_o^2 / 2} \right]$$

for small potential near sheath edge

Bohm sheath criterion

$$v_o \geq u_B = \left(\frac{T_e}{m_i} \right)^{1/2} \rightarrow \left(\frac{T_e + T_i}{m_i} \right)^{1/2} = c_S$$

Bohm velocity-->sound speed

Presheath and Sheath Potentials

• Potential drop across the presheath accelerating the ions to the Bohm velocity where Φ_p is the plasma potential with respect to the sheath-presheath potential.

$$\frac{1}{2} m_i u_B^2 = e\Phi_p$$

• Substituting for the Bohm velocity $e\Phi_p = \frac{T_e + T_i}{2}$: plasma potential

• Density at the sheath edge to that in the plasma from Boltzmann relation

$$n_o = n_b e^{-e\Phi_p/T_e} \approx 0.61 n_b$$

Sheath potential at a floating wall from the ambipolar diffusion condition

$$\Gamma_i = n_o u_B = \Gamma_e = \frac{1}{4} n_o \exp^{e\Phi_w/T_e} \bar{v}_e$$

where the mean electron velocity, $\bar{v}_e = (8T_e/\pi m_e)^{1/2}$

Solving for the wall potential Φ_w,

$$e\Phi_w = -\frac{T_e}{2} \ln\left[\frac{m_i / m_e}{2\pi(1 + T_i / T_e)}\right]$$

wall potential

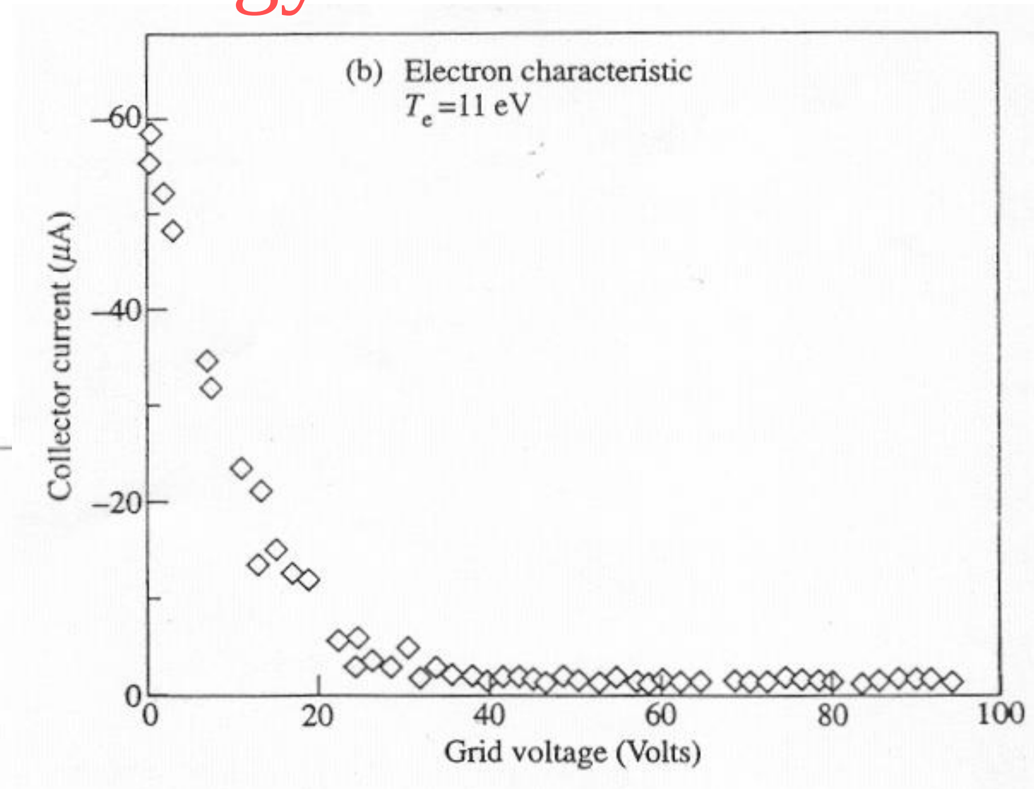
including secondary electron emission effects

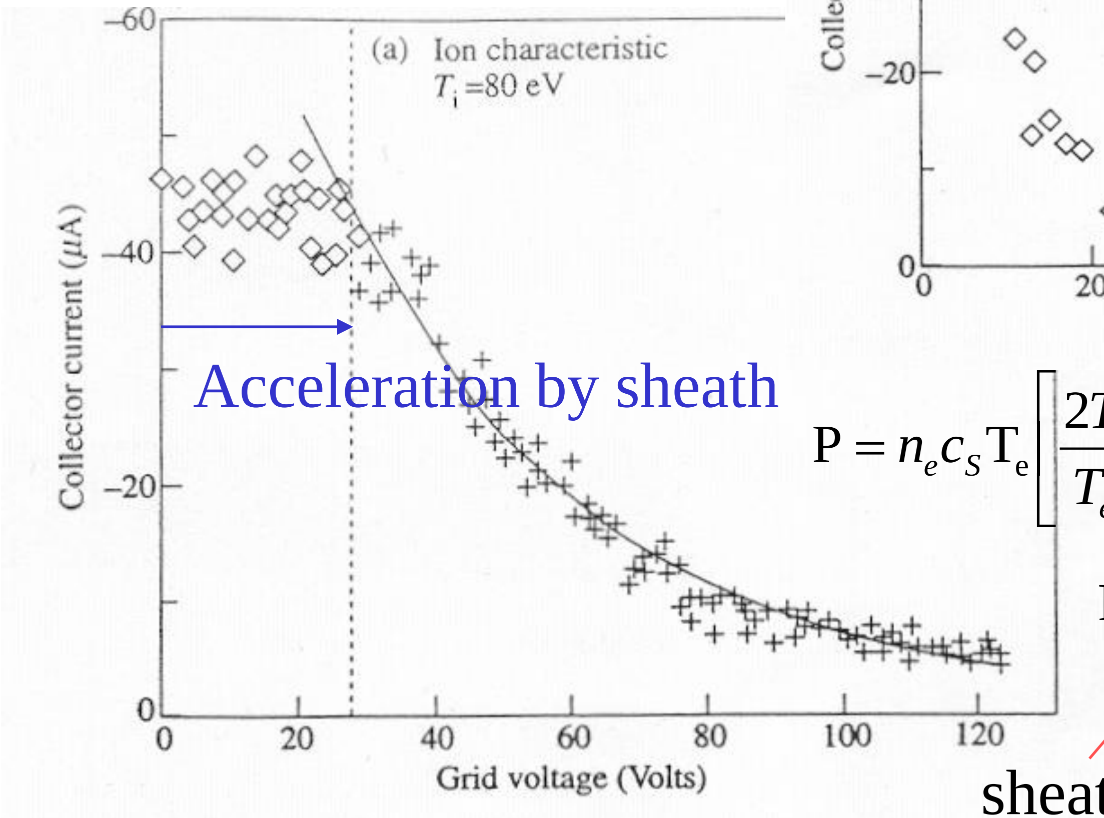
$$e\Phi_w = -\frac{T_e}{2} \ln\left[\frac{(1-\delta^2) m_i / m_e}{2\pi(1 + T_i / T_e)}\right]$$

total secondary emission coefficient, δ

Plasma Ion Energy at the Surface

thermal energy
+ sheath potential





Acceleration by sheath

$$P = n_e c_S T_e\left[\frac{2T_i}{T_e} + \frac{2}{1-\delta} + \frac{1}{2}\ln\left(\frac{(1-\delta^2)m_i / m_e}{2\pi(1+T_i / T_e)}\right)\right]$$

$$P = \gamma_s \Gamma T_e$$

ion flux density

sheath power transmission factor

Scrape-Off Layer: radial distribution

In steady-state, particle balance gives $\frac{d}{dr}\left[D_\perp \frac{dn}{dr}\right] = \frac{nc_S}{L_c}$

$$n(r) = n(a)\exp[-(r-a)/\lambda_n]$$

with scrape-off thickness, or e-folding length, for density $\lambda_n = \left[\frac{D_\perp L_c}{c_S}\right]^{1/2}$

Similarly, electron heat balance gives $T_e(r) = T_e(a)\exp[-(r-a)/\lambda_T]$

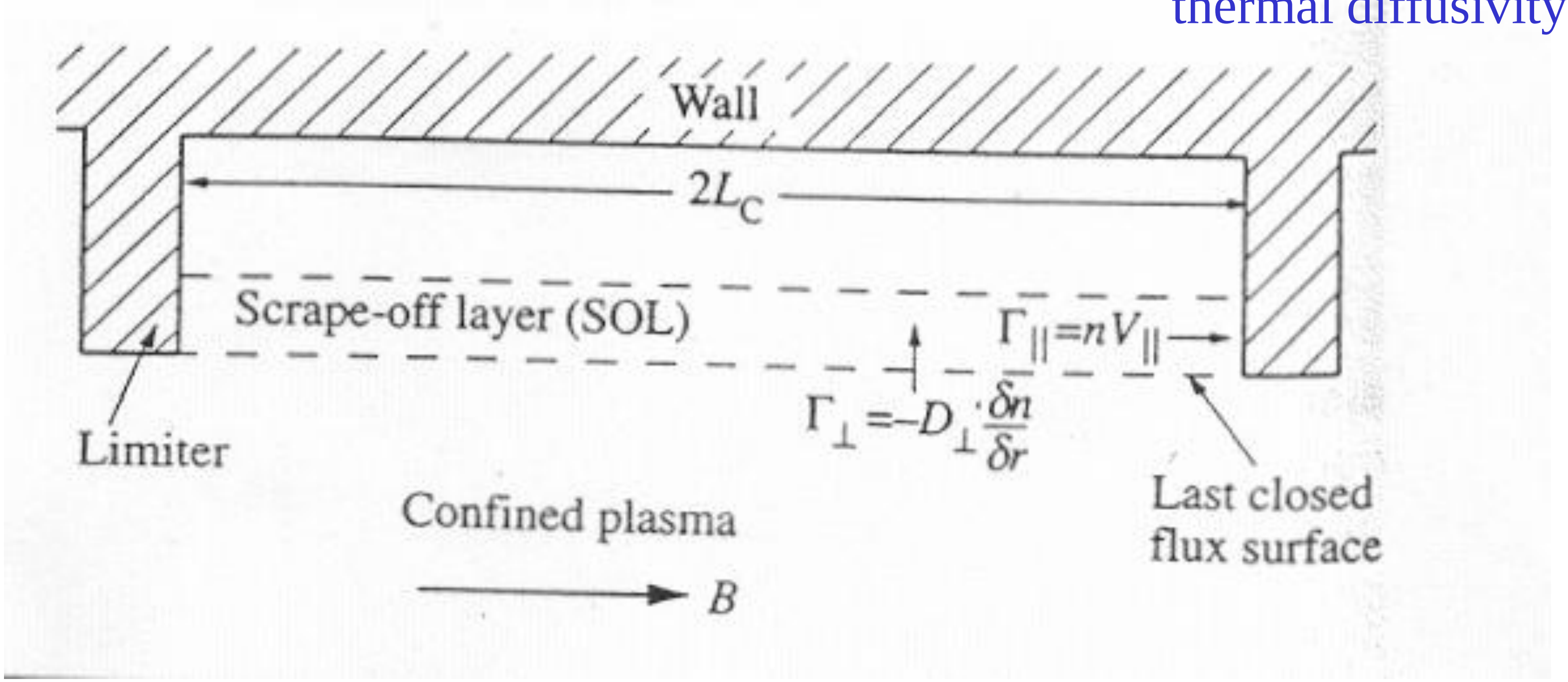
where

$$1 + \frac{\lambda_n}{\lambda_{Te}} = \frac{\delta}{5/2 + \chi_\perp \lambda_n / D_\perp \lambda_{Te}}$$

$$\left.\begin{matrix}\lambda_n \\ \lambda_{Te}\end{matrix}\right\} \rightarrow \left\{\begin{matrix}D_\perp \\ \chi_\perp\end{matrix}\right.$$

Cross field diffusion coefficient

Cross field thermal diffusivity



Scrape-Off Layer : global balance

Global particle and energy balance :
total particle outflux = total flux to limiter

$$\Gamma_n = \frac{\bar{n}V}{\tau_p} = \Gamma_L = 4\pi a \int_a^\infty n(r)dr$$

$$n(a) = \frac{\bar{n}V}{\tau_p} \frac{1}{4\pi a \lambda_n c_S}$$

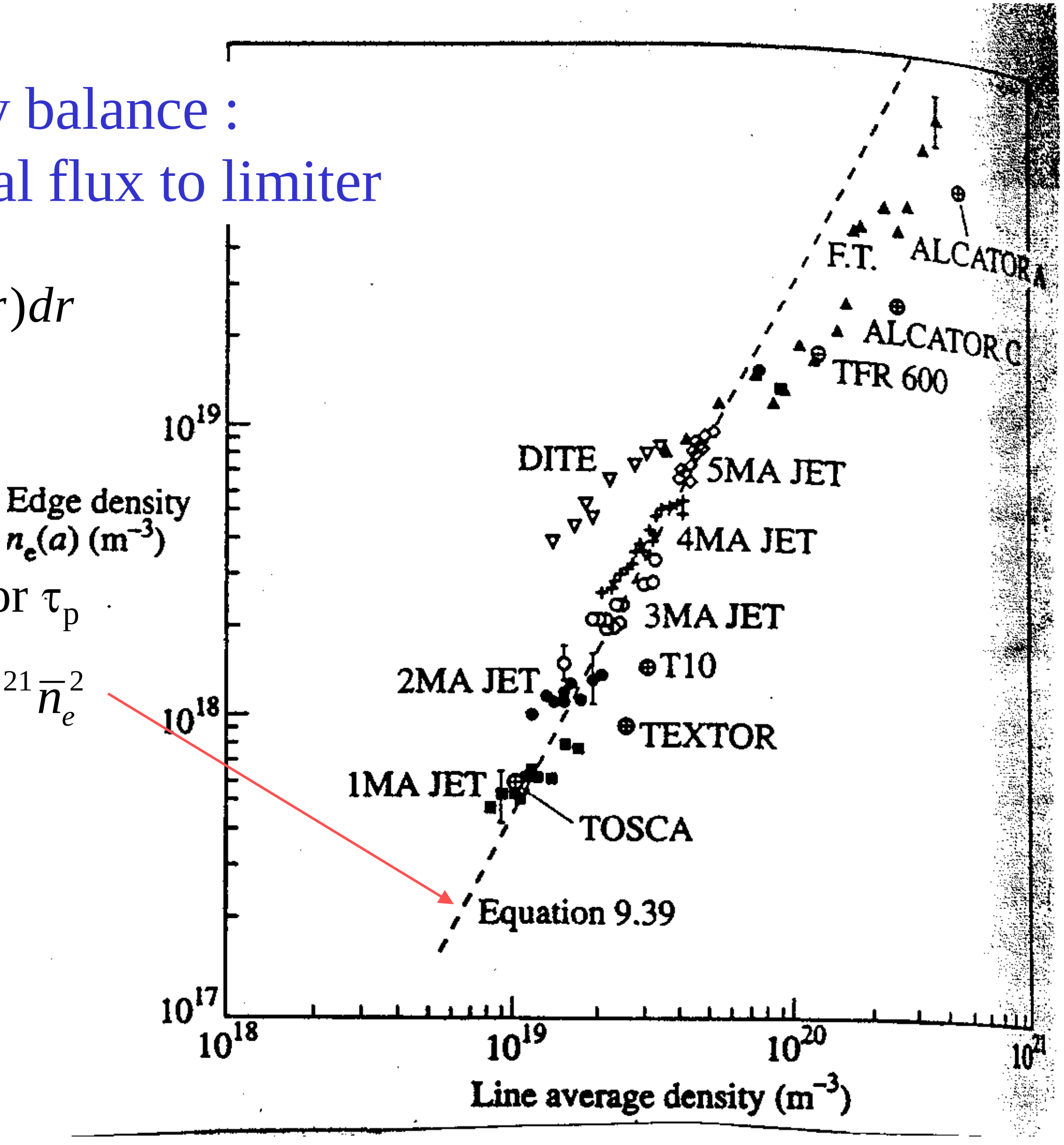
simple edge transport model for τ_p

$$n(a) = \frac{<\sigma v_i>}{6\bar{v}_n} \lambda_\Gamma \bar{n}^2 \approx 5\times 10^{21} \bar{n}_e^2$$

ionization rate coefficient

initial neutral velocity

flux e-folding length



Parallel Transport outside the LCFS

Isothermal fluid model

For steady-state, inviscid, isothermal, 1-D flow,
particle and momentum conservation gives

$$\frac{d}{dz}(nv) = S \qquad nmv\frac{dv}{dz} = -\frac{dp}{dz} - mvS$$

$$\longrightarrow \frac{dM}{dz} = \frac{S}{nc_S}\frac{1+M^2}{1-M^2} \qquad M = v/c_S$$ Mach number

$$\frac{d}{dz}(p + nmv^2) = 0$$ so that $$\frac{n(M)}{n(0)} = \frac{1}{1+M^2}$$

$n(0)$: density at stagnation point

Plasma potential by considering Boltzmann distribution of electron density

$$n(M) = n(0)\frac{1}{1+M^2} = n(0)\exp(e\Phi(M)/T_e)$$

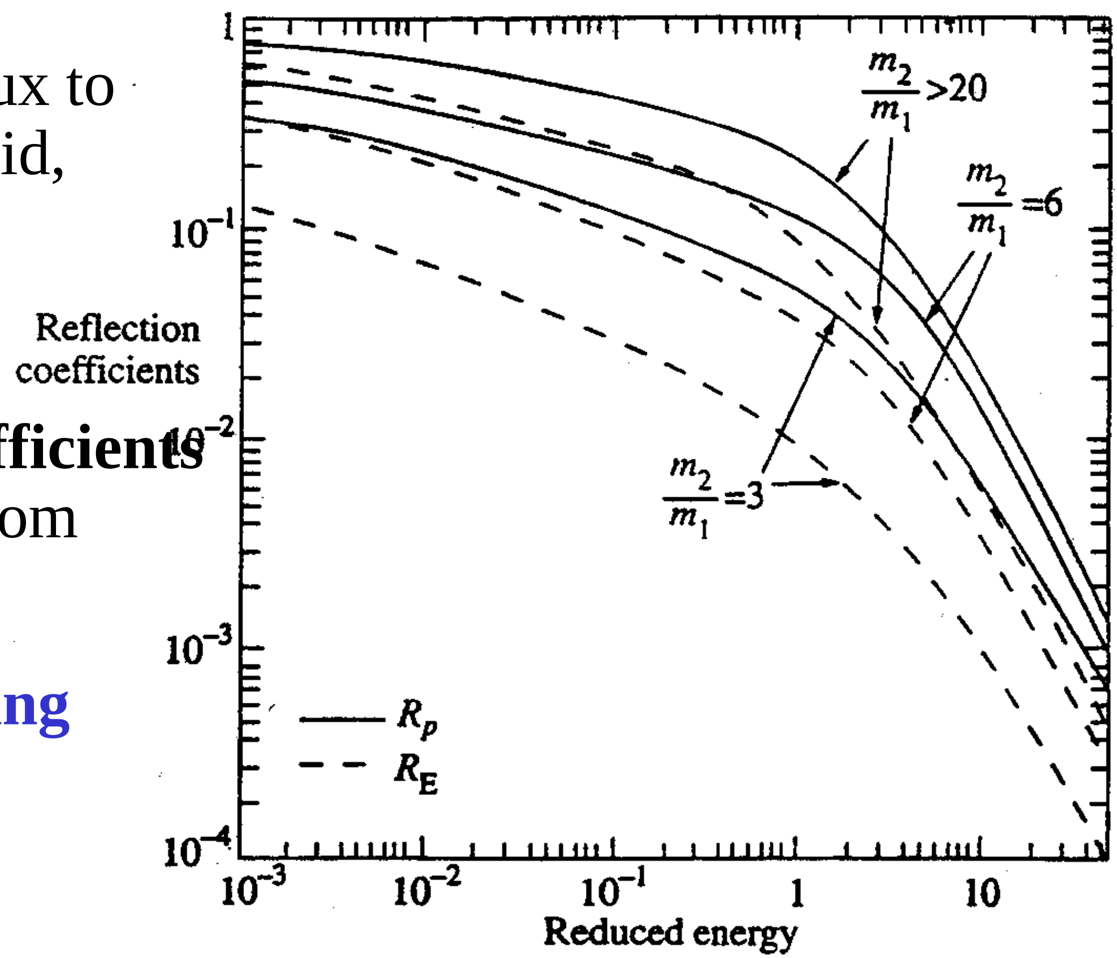
$$\longrightarrow \Phi(M) = -\frac{T_e}{e}\ln(1+M^2)$$

Flow velocity is difficult to calculate and there is little experimental information

Recycling

Recycling : each plasma goes to the divertor target plate or limiter and returns to the plasma many times during the discharge

Recycling coefficient :
ratio of the returning flux to the plasma from the solid, to the incident flux

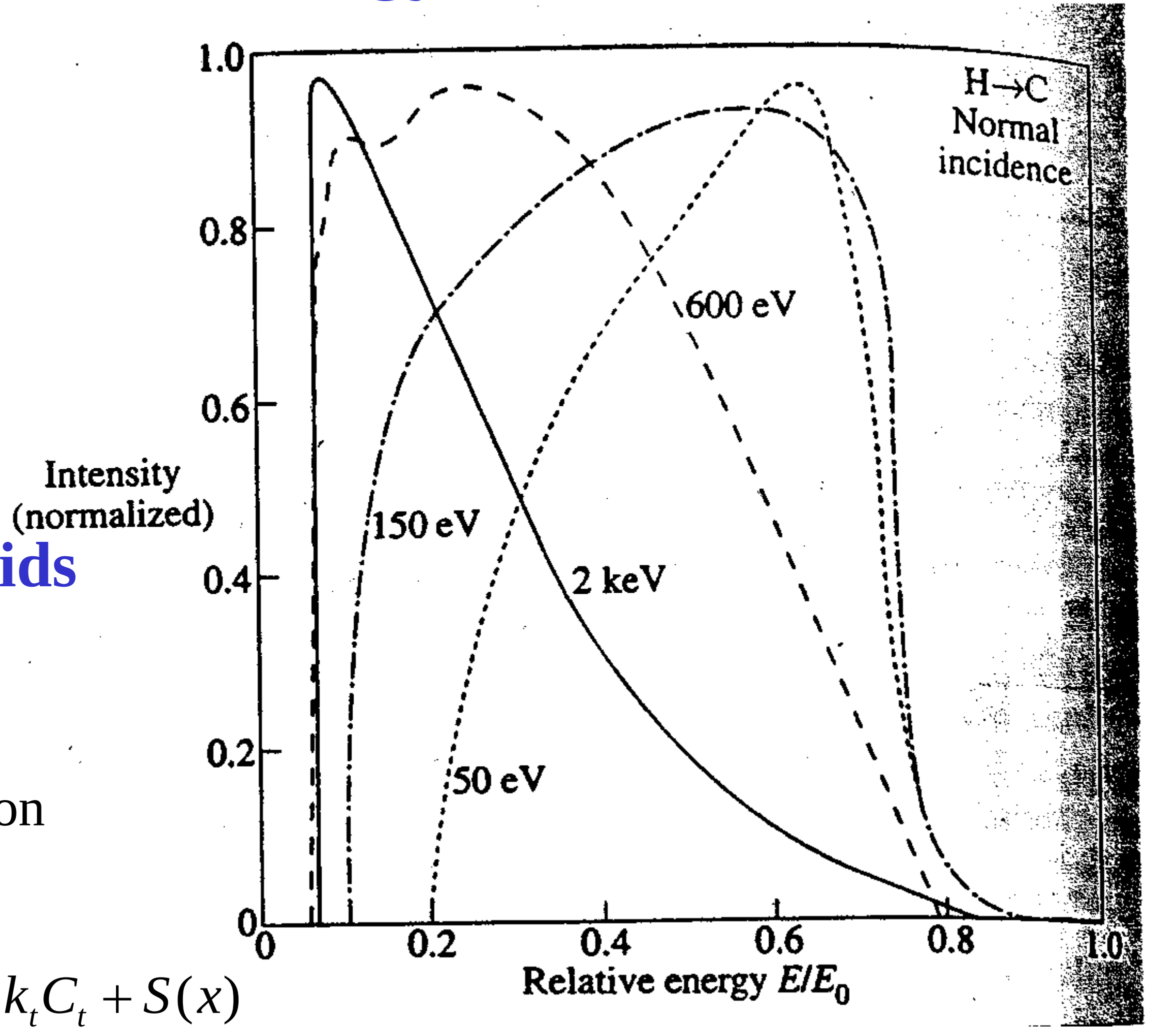


Efficient recycling coefficients
with additional influx from adsorbed particles (>1)

- **Particle backscattering coefficients, R_p**
- **Energy reflection coefficients, R_E**

Recycling:
backscattered ion energy distribution

• Backscattered particles are predominantly **neutral**
• **Average energy** depends on $\mathbf{R_E/R_p}$



Hydrogen diffusion in solids
- exothermic : trap
- endothermic :escape

Rate coeff. of thermal desorption
Rate coeff. of entering trap

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial x^2} - k_{st}C(C_{T0} - C_t) + k_t C_t + S(x)$$

$$\frac{\partial C_t(x,t)}{\partial t} = k_{st}C(C_{T0} - C_t) - k_t C_t$$

b.c. $D\frac{\partial C}{\partial x}\bigg|_{x=0} = k_r C(0)^2$

Plasma-Surface Interacting Processes

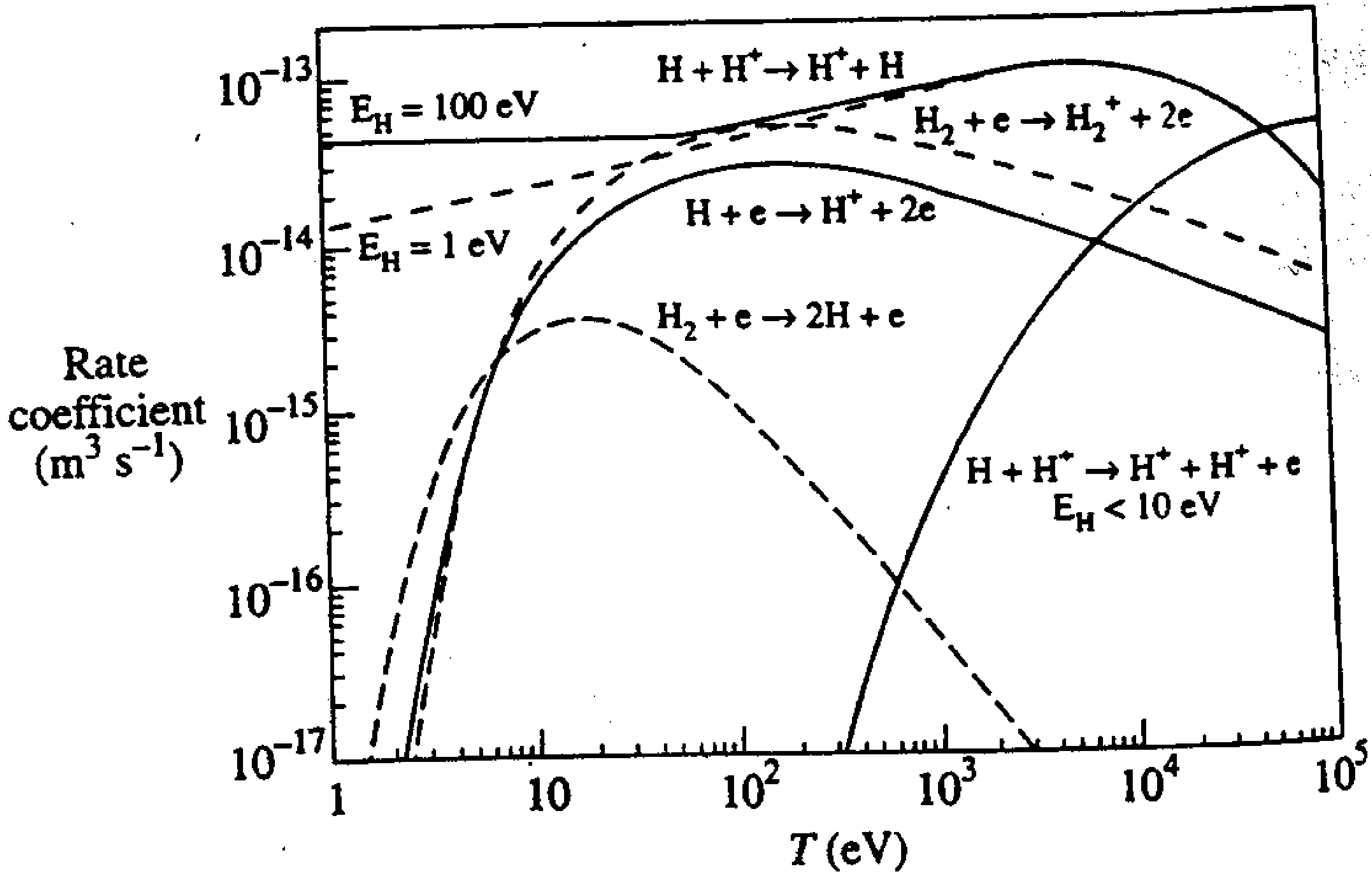
- Atomic and molecular processes
- Desorption : Wall conditioning
- Sputtering
- Arcing
- Evaporation

Atomic and Molecular Processes

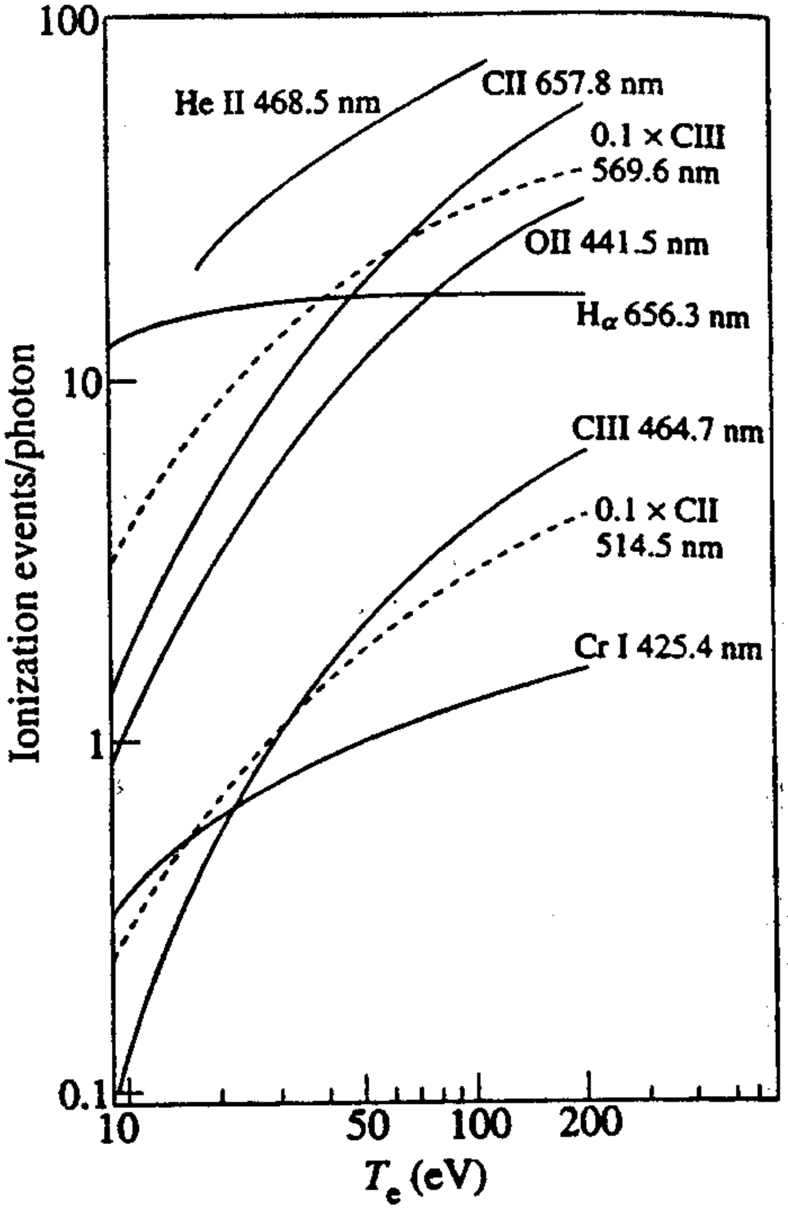
- Atomic reactions
  - excitation $H + e$ --> $H^* + e$
  - ionization $H + e$ --> $H^+ + 2e$
  - charge exchange $H^+ + H$ --> $H + H^+$
- Molecular reactions
  - dissociation $H_2 + e$ --> $H + H + e$
  - dissociative ionization $H_2 + e$ --> $H^+ + H + 2e$
  - $H_2^+ + e$ --> $H^+ + H^+ + 2e$
  - molecular ionization $H_2 + e$ --> $H_2^+ + 2e$
  - dissociative recombination $H_2^+ + e$ --> $H + H$

Atomic and Molecular Processes

- Relative reaction rates depend on plasma temperature and density
- Rate coefficients for hydrogen atoms and molecules



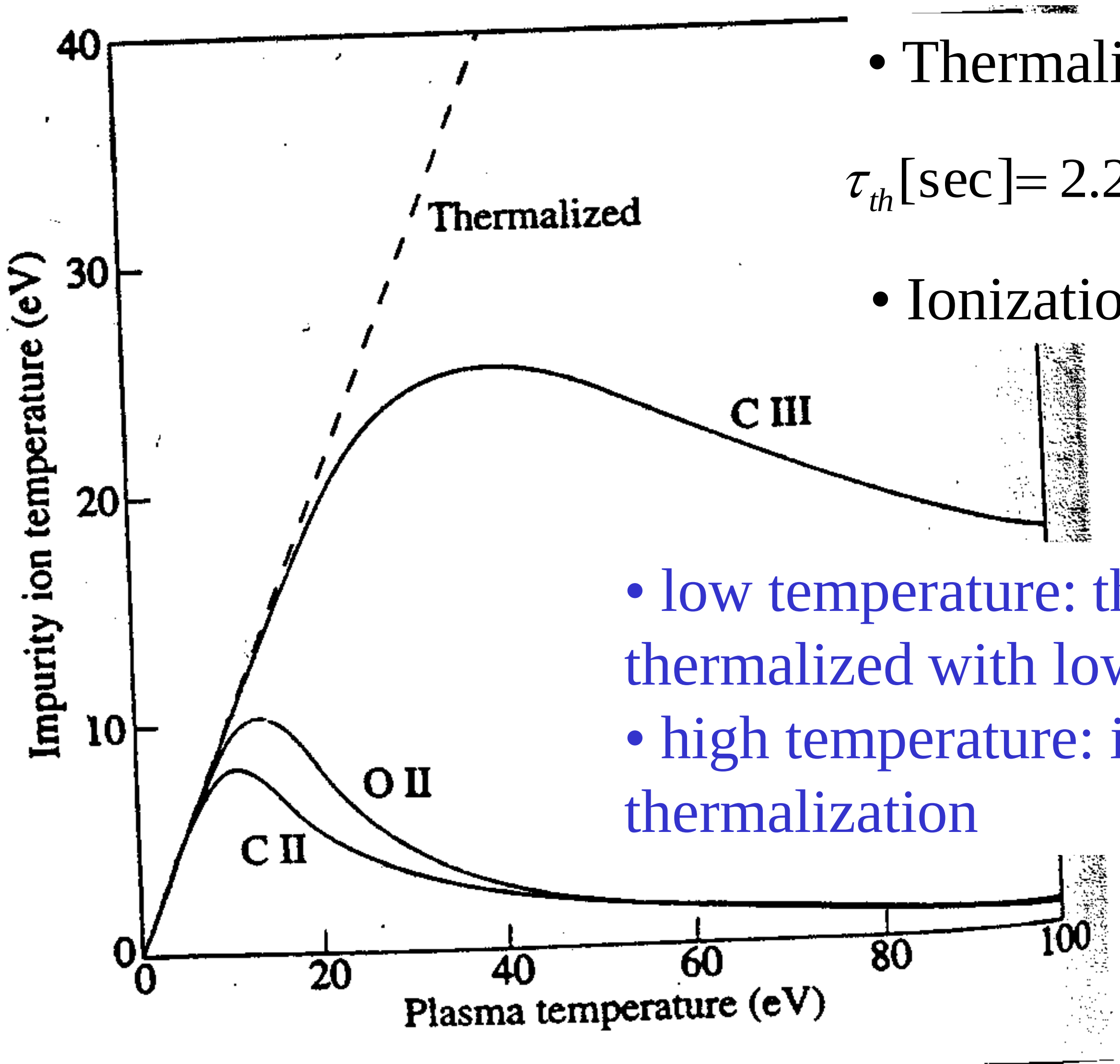
Atomic and Molecular Processes



- Ionization and charge exchange influence the transport of recycling species and impurity species
- Charge exchange dominant hydrogen processes : random walk diffusion
- Ionization dominant impurity ions are multiply ionized
- Dominant charge states of the impurity determined by electron temperature, electron density, and residual time
- Photon efficiency
  - ion influx with absolute radiation
  - average energy loss per ionization
- Inverse photon efficiency

Impurity Ion Temperature

Calculated temperature of some typical impurity ion species as a function of background plasma temperature



- Thermalization time

$$\tau_{th}[\text{sec}] = 2.2\times 10^{17} \frac{m_I T_B^{3/2}[keV]}{m_B^{1/2} n_B Z_B^2 Z_I^2 \ln\Lambda}$$

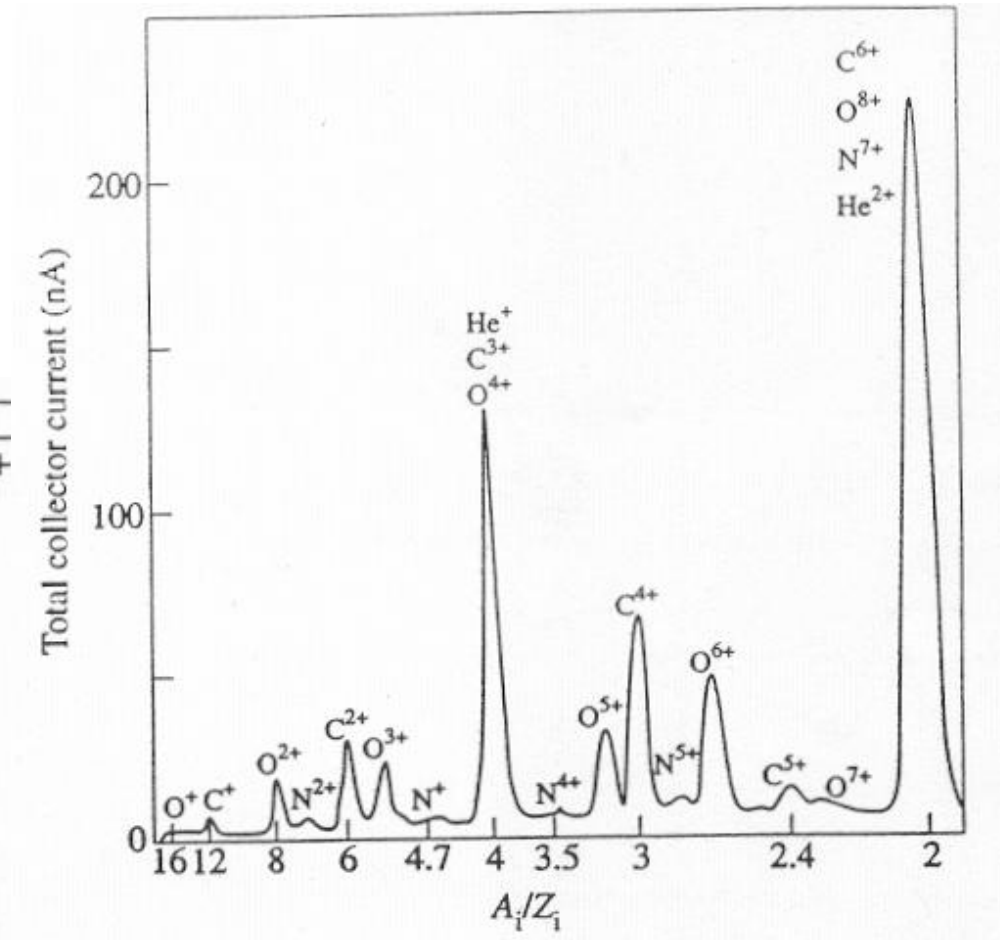
- Ionization time

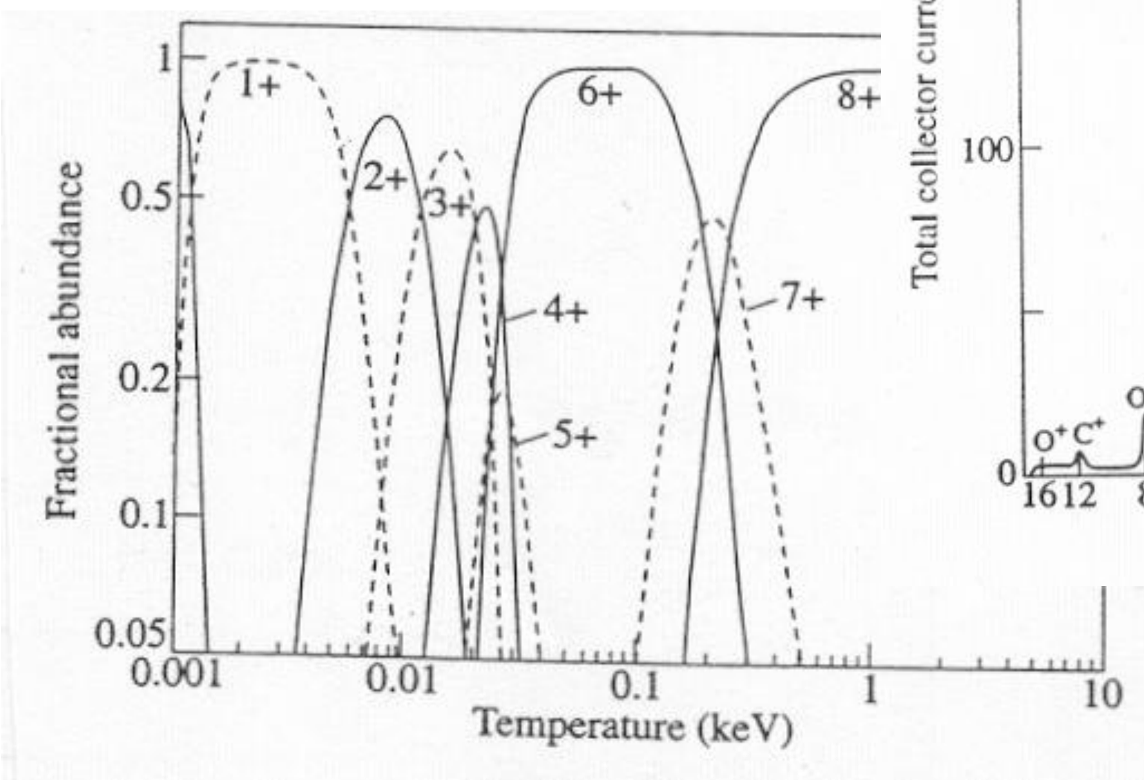
$$\tau_{ion} = (n_e < \sigma v >_{ion})^{-1}$$

- low temperature: the impurities are quickly thermalized with low ionization rates
- high temperature: ionization occurs before thermalization

Charge State Distribution of Impurity Ion Species

Local electron temperature determines the charge state





Oxygen ionization state distribution in coronal equilibrium

Adsorption and Desorption

- Adsorbed atoms: hydrogen, carbon monoxide, water, etc
    - weakly bound physical adsorption : ~ 0.3eV
    - strongly bound chemical adsorption : ~ 3eV
- Desorbed by incident ions, neutrals, electrons and photons
    - electron and photon processes : electronic, weak
    - ions and neutrals : by momentum transfer, strong cross section σ up to 10^{-18}m^2, yield $Y = \sigma c J \exp(-J\sigma t)$

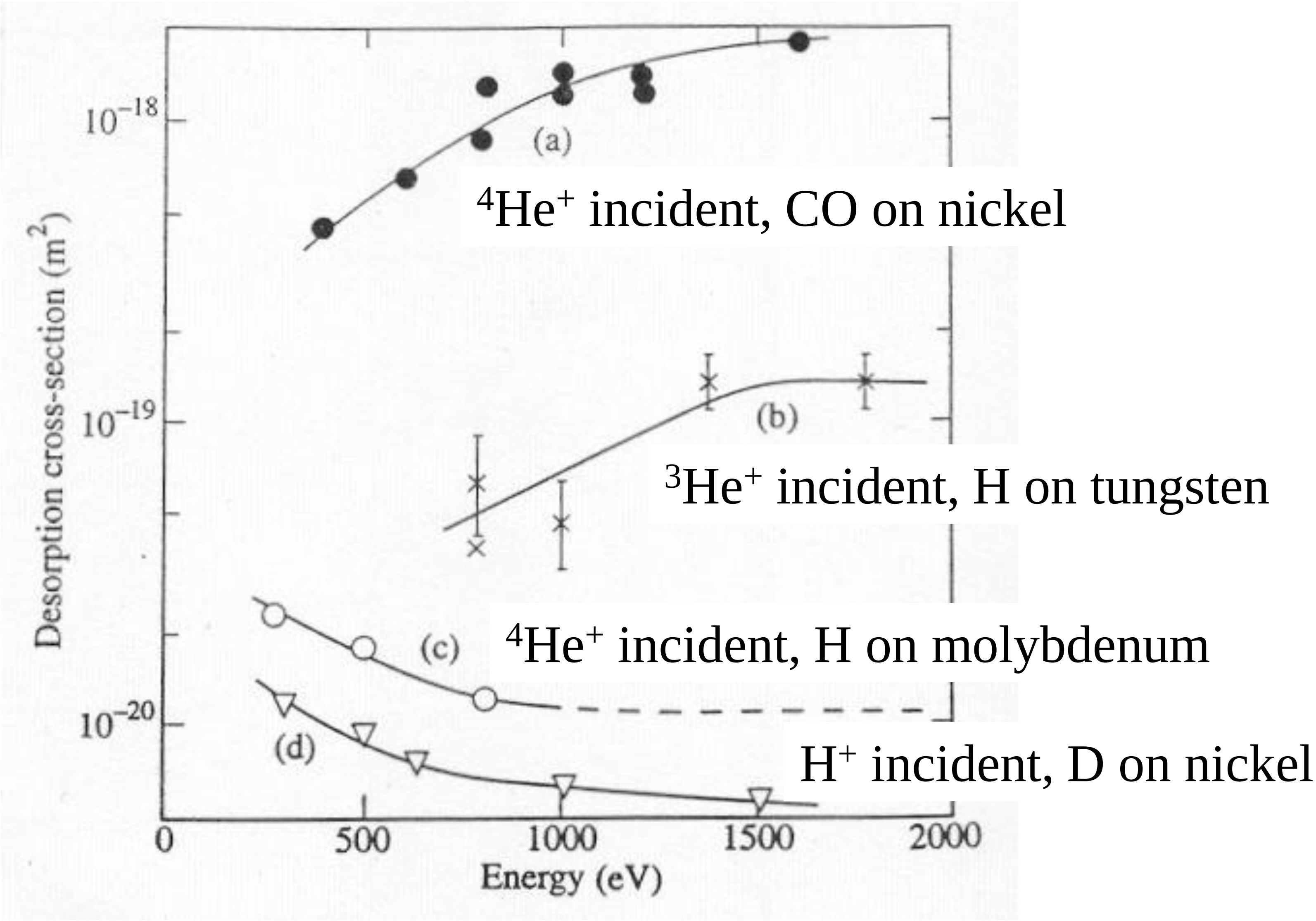
surface concentration (c)

Incident ion flux density (J)

- Desorption can lead to
    - impurity accumulation in the plasma
    - lack of density control when plasma species desorbed

→ **need wall conditioning**

Energy Dependency of Desorption Cross Section



Wall Conditioning

- Baking the vacuum vessel, typically to 200-350°C
- Discharge cleaning
  - surface cleaned by particle bombardment in discharges
  - glow discharges: effective and simple, combined with RF operating at lower pressure of 0.1Pa
  - pulsed discharges: tokamak ohmic discharge w/o TF
  - ECR discharges: resonance location can be varied
  - enhanced cleaning with hot vessel with less readsorption
  - light ions such as hydrogen(with chemical action) and helium(remove oxygen and hydrogen with carbon walls) are used to avoid sputtering
- Gettering: wall covered with a metal film by evaporation
- Carbonization and boronization: covering wall with low Z

→

- Wider operating range up to higher densities w/o excessive radiation
- High density and low temperature decrease sputtering yields

→ not applicable for reactor

Gettering with Thin Metallic Film

Wall covered with a clean metal film by evaporation

•**remove unwanted impurity species** : fresh layers of chemically active metals react with active gases such as O_2, CO, H_2, and CO_2 binding them tightly to the surface

• **reduce outgassing** : sequential deposition bury the adsorbed gases

Materials for gettering

- high chemical reactivity and high vapor pressures at modest temperatures, typically 1500-2000°K : **titanium**, chromium
- beryllium : good getter, low atomic number, but high toxicity

Disadvantages

- should cover at least 30% of the vacuum vessel surface
- quick saturation and need getter between shots
- film flakes with the size of 10-100μm: random impurity injection

Carbonization and Boronization

Cover the tokamak wall with low Z non-metallic films(C & B) to minimize the release of high Z impurities

- **Carbonization**
  - gaseous carbon compound(CH_4) --> glow discharges --> deposit a thin layer of amorphous carbon on the wall (optimum temp. 300℃)
  - initially increasing the hydrogen --> make density control difficult --> recycling control with helium glow discharge after carbonization
  - optimum thickness for good adhesion ~1μm --> short lifetime
- **Boronization**
  - similar to carbonization with boranes(B_2H_4, B_2H_6) at 400℃ --> boron acts as getter and thin boron films pump oxygen and hydrogen
  - Trimethyl borone, $B(CH_3)_3$, forms mixed films of carbon and boron
  - low affinity of boronized surface for water vapor(good for opening)
  - silane(SiH_4) deposit Si film : good getter, but higher atomic number
  - disadvantages : toxicity of both borane and silane

Sputtering

Removal of atoms from the solid surface by the impact of ions or atoms, resulting in impurity radiation and surface erosion

Sputtering yields

- decreases with increasing sublimation energy
- increase with increasing energy transfer

Threshold energy

$$E_T = \frac{E_s}{\gamma_{sp}(1-\gamma_{sp})}$$

reflection

$$\gamma_{sp} = \frac{4m_1 m_2}{(m_1 + m_2)^2}$$

$m_{1,2}$: masses of incident and target atoms

Sputtering yields simulated by Monte Carlo code

- linearly increases after threshold until saturated
- decreases at higher energy since collision cascade occurs away from the solid surface in deeper location
- maximum yield move to higher energy as target mass increases
- magnitude of sputtering yield depends on surface binding energy
- surface structure and impurity level can change the binding energy

Energy Dependence of Sputtering Yield

General semi-empirical curve for sputter yield

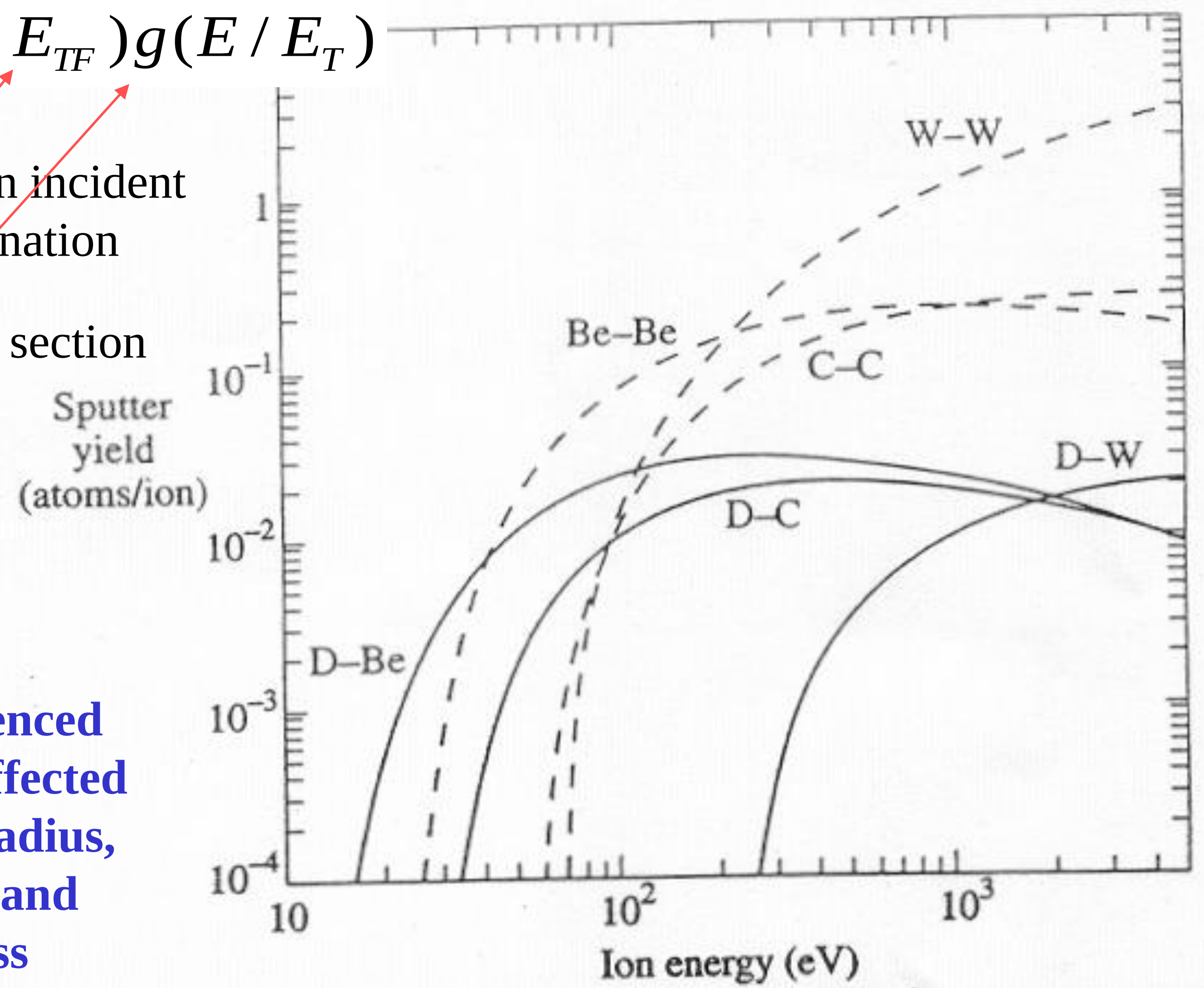
$$Y(E) = QS_n(E/E_{TF})g(E/E_T)$$

yield factor depends on incident and target atom combination

nuclear stopping cross section

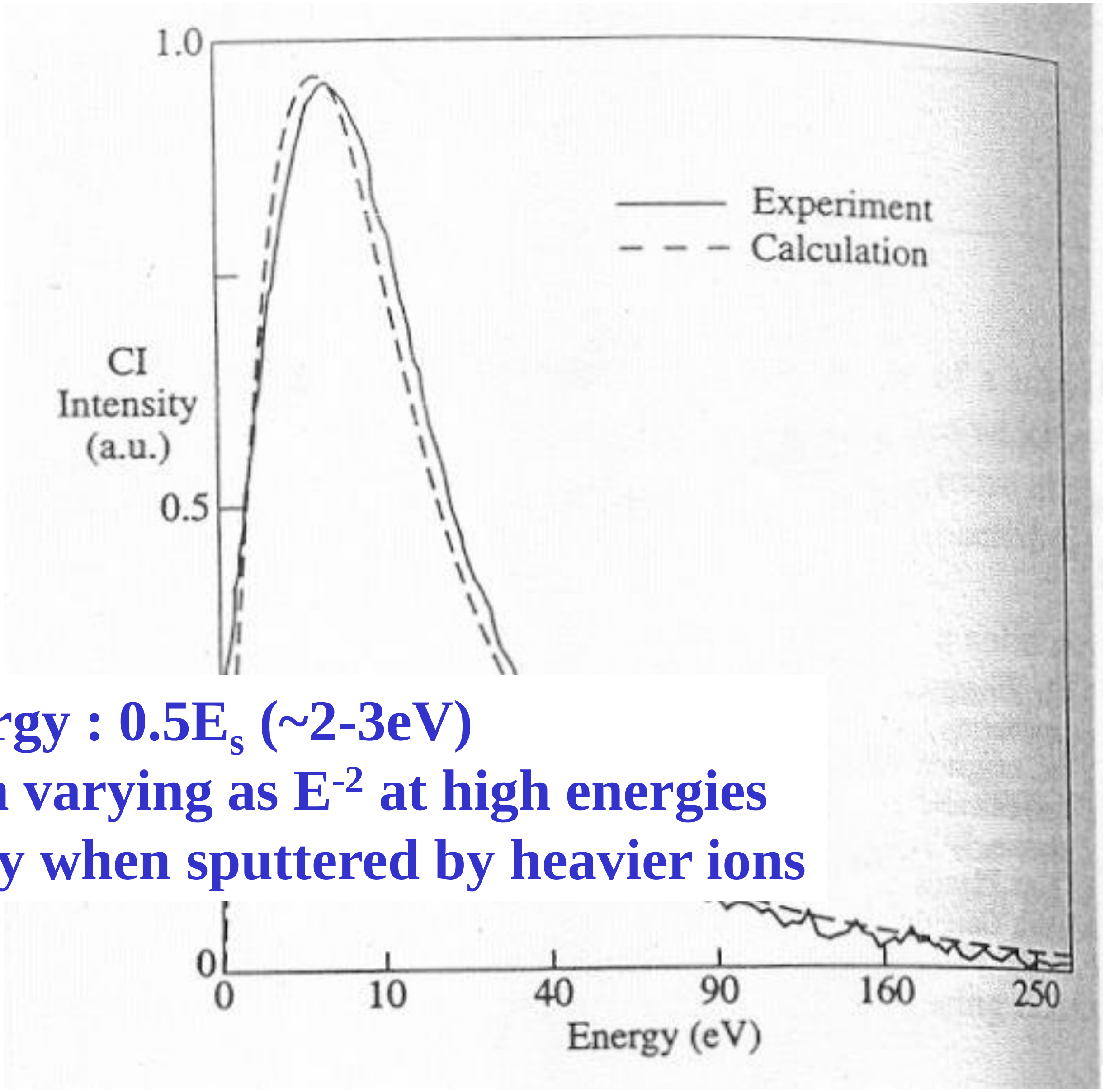
Thomas-Fermi energy

threshold function



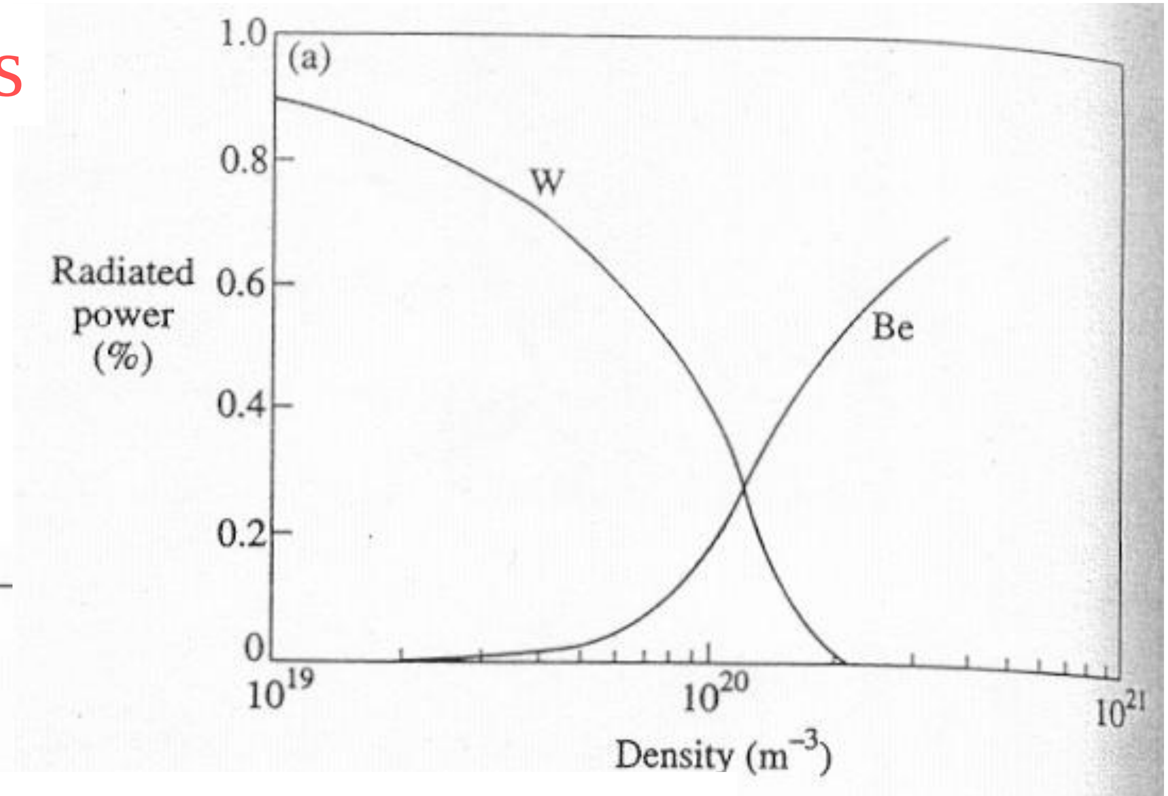
- **Sputter yield influenced by incident angles affected by the ion Larmor radius, sheath acceleration, and the surface roughness**

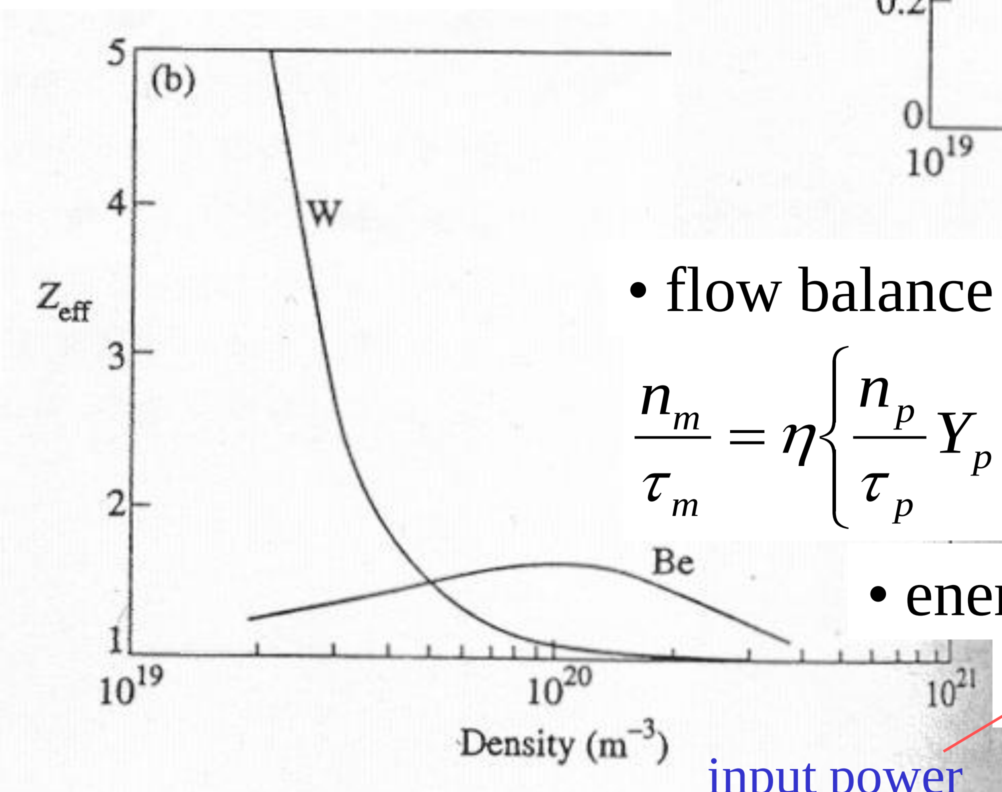
Energy Distribution of Sputtered Atom



- most probable energy : $0.5E_s$ (~2-3eV)
- energy distribution varying as E^{-2} at high energies
- higher mean energy when sputtered by heavier ions

Sputtering Models





- flow balance in steady-state

$$\frac{n_m}{\tau_m} = \eta \left\{ \frac{n_p}{\tau_p} Y_p + \frac{n_m}{\tau_m} Y_m \right\} \rightarrow \frac{n_m}{n_p} = \eta \frac{\tau_m}{\tau_p} \frac{Y_p}{1 - \eta Y_m}$$

- energy balance

$$P_H - P_R = P_C = \gamma_s T_e(a) n_p V / \tau_p$$

input power

radiated power

energy transported to the surface per e-i pair

Choice of Materials

- **impurity production rates**
- **structual strength**
- **neutron activation**
- **thermal shock resistance**

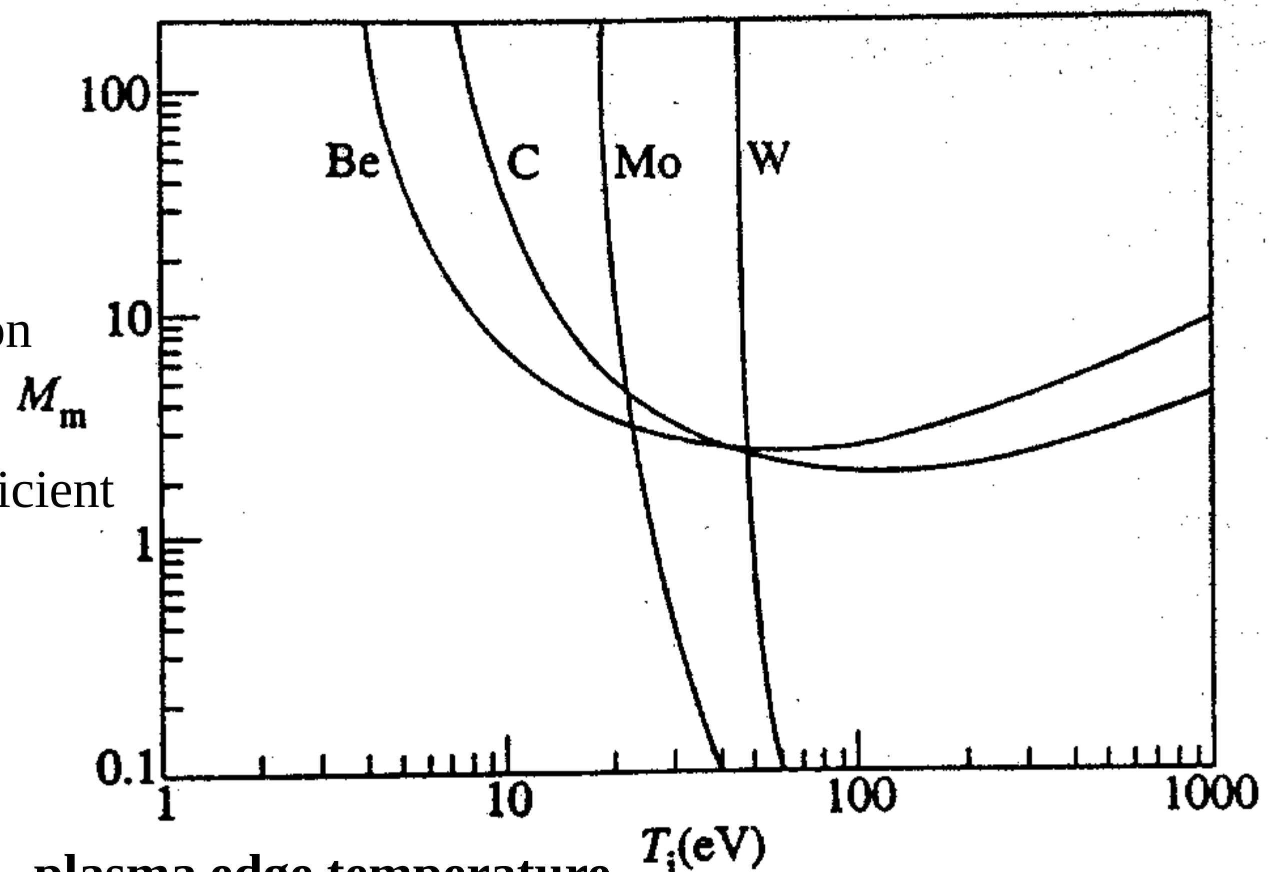
minimize Z and sputter yield

- **figure of merit**

$$M_m = f_i \frac{1 - Y_m}{Y_p}$$

maximum allowed impurity concentration

plasma sputtering coefficient



plasma edge temperature

Arcing

Sustained with low voltage, high current

→ Joule heating, evaporation

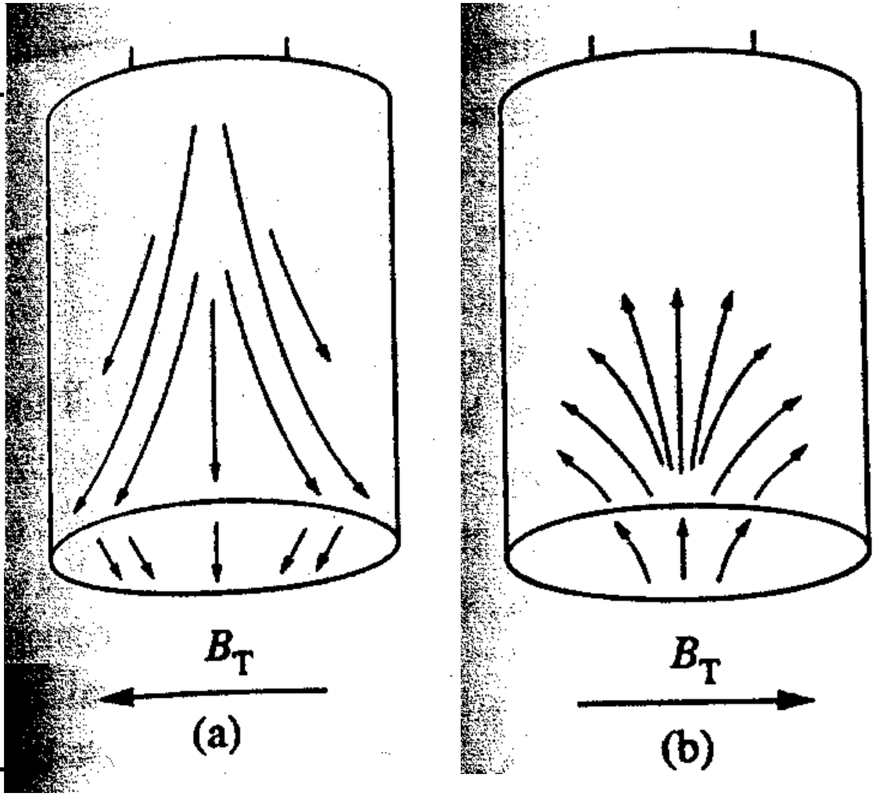
→ erosion

- **Power arc** by external potential
- **Unipolar arc** by plasma sheath

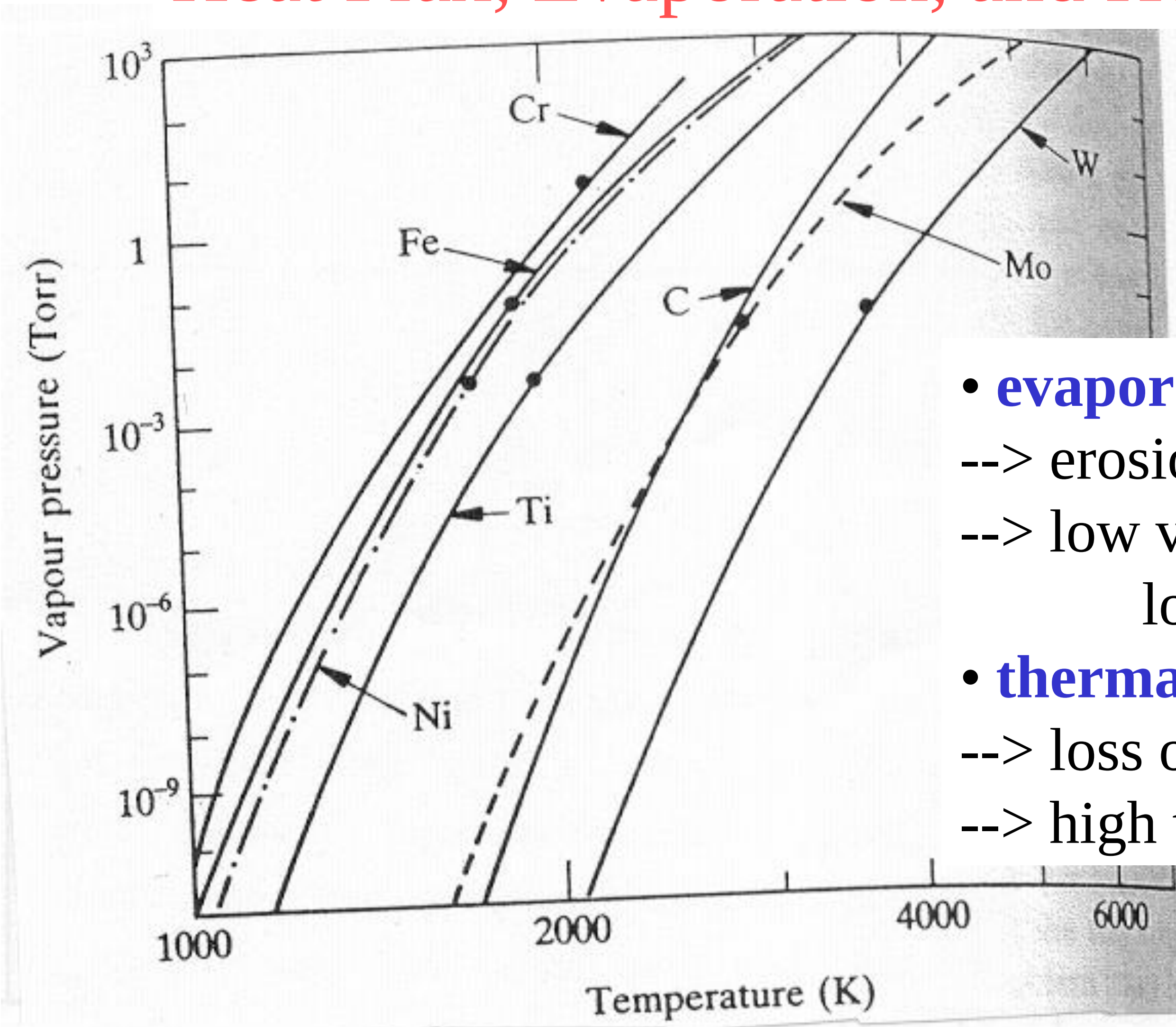
Ion currents : 7-10%, 50-100eV, in charge states up to 4-5

Table 9.8.1 Erosion due to arcing

Element	Erosion rate 10^{-7} kg/C
Cadmium	6.55
Zinc	2.15
Aluminium	1.2
Copper	1.15
Nickel	1.0
Silver	1.5
Iron	0.73
Tungston	0.62
Titanium	0.52
Chromium	0.4
Molybdenum	0.47
Carbon	0.17



Heat Flux, Evaporation, and Heat Transfer



- **evaporation**

--> erosion, contamination

--> low vapor pressures

low sputtering yield

- **thermal shock**

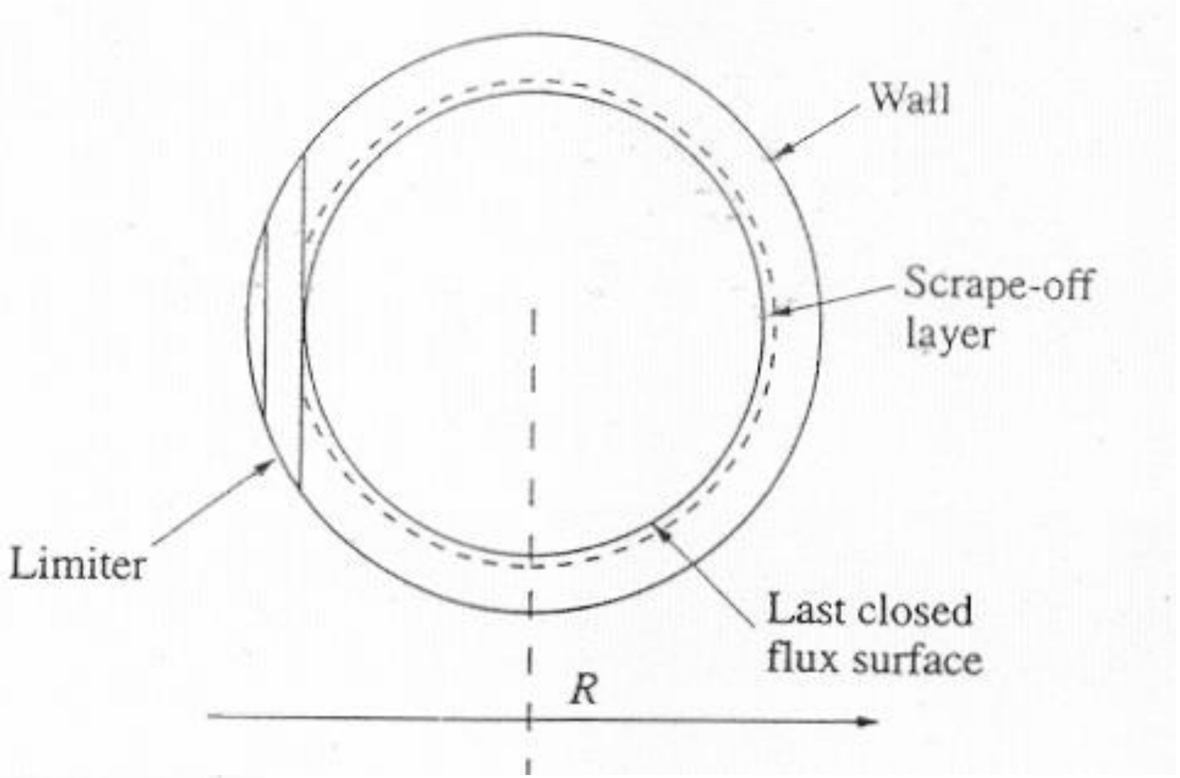
--> loss of structual strength

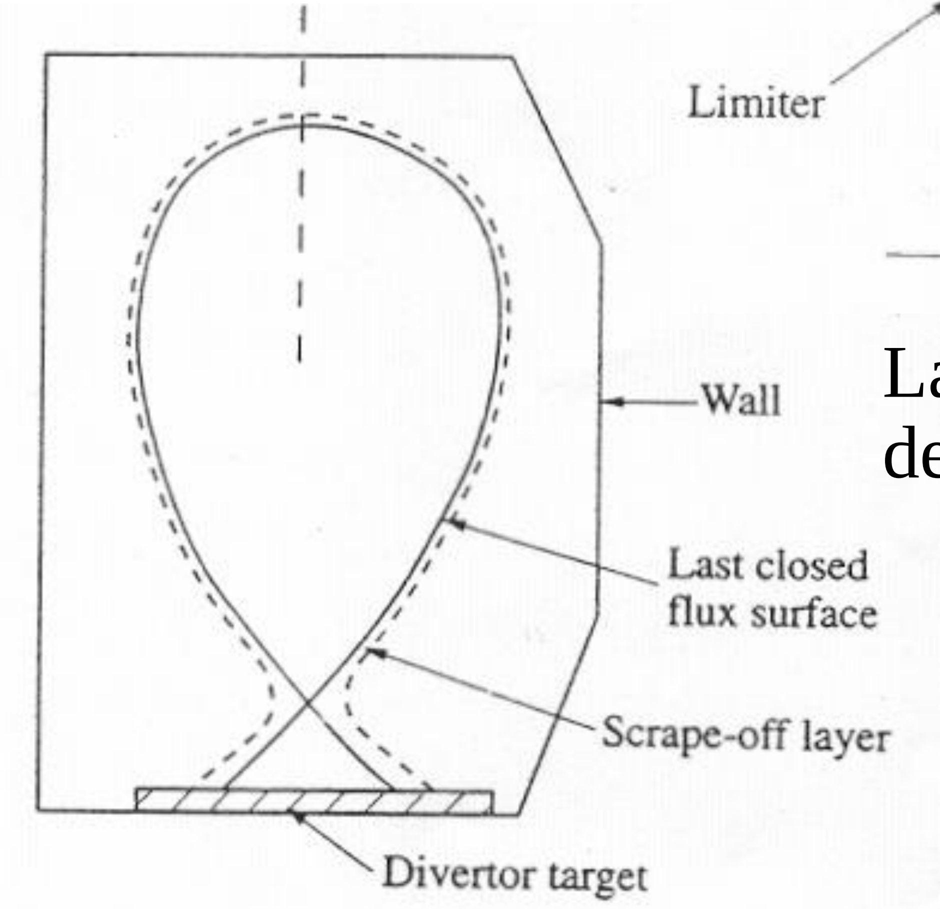
--> high thermal conductivity

Upper limit of tolerable heat flux : 10-20MW/m²

Heat flux for high reliability : 2-5MW/m²

Plasma-Surface Interactions





Last Closed Flux Surface(LCFS) determined by

- Limiters
- Divertors

Tritium Behavior

Limiters define plasma boundary

Roles of the limiter

- **protect the wall from the plasma : disruptions, runaway electrons, other instabilities -->high heat loads --> refractory material**
- **localize the plasma-surface interaction**
- **localize the particle recycling : high neutral density and radiation**

Material selection criteria for the limiter

- **withstand thermal shock**
- **produce as low an impurity flux as possible**
- **maintain low atomic number with impurity**
- **have good thermal conductivity for heat transfer**

Materials for the limiter

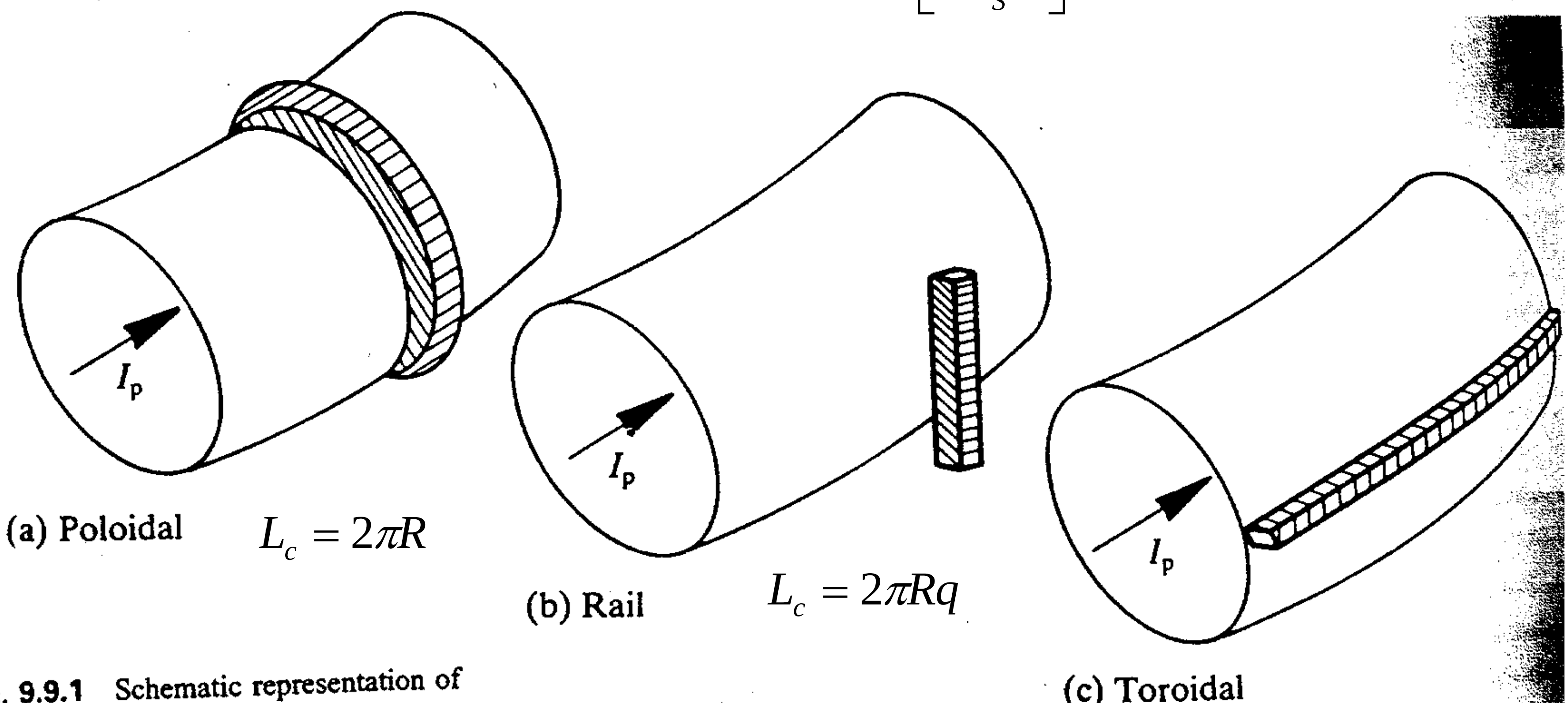
- **low Z materials : carbon and beryllium, high heat loads**
- **high Z materials : tungsten and molybdenum, good thermal properties, low sputtering yields; however, very low concentrations allowed because of their high Z**

Limiters

Different types of limiters have different

- **connection lengths**
- **scrape-off layer decay lengths**

$$\lambda_n = \left[\frac{D_\perp L_c}{c_S}\right]^{1/2}$$



$L_c = 2\pi R$

$L_c = 2\pi Rq$

Fig. 9.9.1 Schematic representation of different types of limiter.

For long pulse/steady state operation, thermal capacity become important

→ **toroidal limiter**(spread the heat load) **or divertor**(impurity shielding)

Divertors define the LCFS solely by the magnetic field and isolate plasma surface interactions from the confined plasma

Possible ways of reducing power density at the target

- **placing the target tiles at an oblique angle to the field lines**
- **flux expansion of the field lines as they approach the target**
- **magnetically sweeping the strike point over a width > λ_p**
- **radiating power before reaching to the target by conduction**
- **transferring the energy to neutral particles in the divertor**

Avoiding target surface erosion as well as impurity flow into plasmas

Objectives of divertor design in the fusion reactor

- **minimizing the impurity content of the plasma by having the plasma surface interactions remote from the confined plasma and designing the divertor particle flow**
- **removing the alpha particle power by heat transfer through a solid surface to a fluid transfer medium**
- **removing the helium ash resulting from the fusion reactions**

One-dimensional Fluid Model of Divertor SOL

Assume

- no energy or momentum sources or sinks (radiation) in the scrape-off layer
- Simplified geometry between X point and the target
- Energy flow from the confined plasma

Momentum conservation

$$nT(1+\gamma M^2) = const. \longrightarrow n_u T_u = 2 n_t T_t$$

Heat transport along the SOL:
electron heat conduction

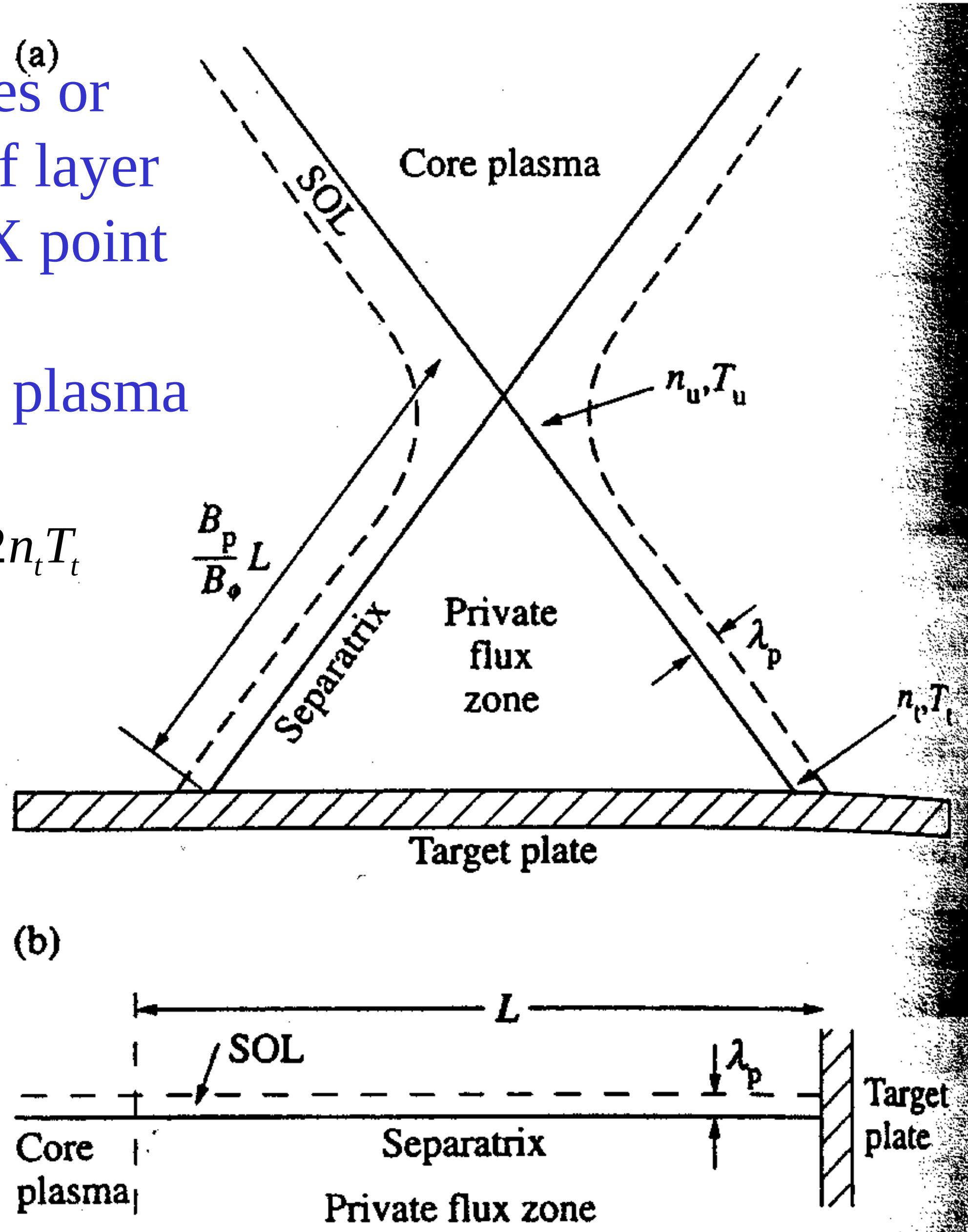
$$\kappa \frac{dT_e}{dz} = -q_{//} \qquad \kappa = \alpha T_e^{5/2}$$

For constant $q_{//}$,

$$T_u^{7/2} = T_t^{7/2} + \frac{7 q_{//} L}{2\alpha}$$

Power density transmitted across the plasma sheath at the target

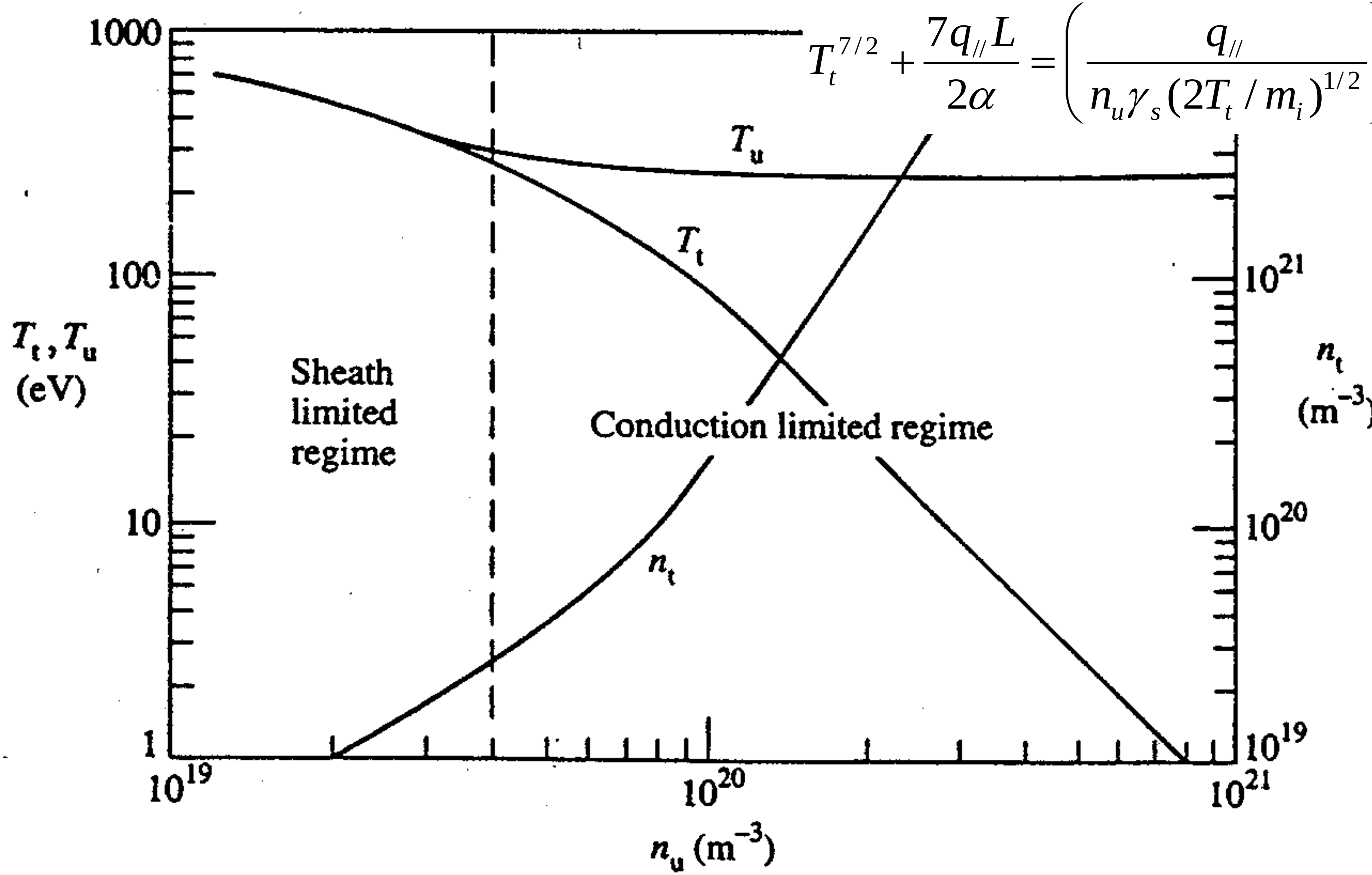
$$q_{//} = \gamma_s n_t T_t c_{st}$$



Solutions

Target temperature

$$T_t^{7/2} + \frac{7q_{//}L}{2\alpha} = \left(\frac{q_{//}}{n_u \gamma_s (2T_t / m_i)^{1/2}} \right)^{7/2}$$



When sufficiently large temperature drop, i.e. $T_u^{7/2} \gg T_t^{7/2}$

$$n_t = 2.7\times 10^{33} \frac{L^{6/7}\gamma_s^2 n_s^3}{Aq_{//}^{8/7}} \qquad T_t = 3.1\times 10^{28} \frac{Aq_{//}^{10/7}}{L^{4/7}\gamma_s^2 n_u^2} \qquad \frac{T_t}{T_u} = 1.9\times 10^{32} \frac{Aq_{//}^{8/7}}{L^{6/7}\gamma_s^2 n_u^2}$$

Radial Power Distribution in the SOL

Steady state power flow in the scrape-off layer

$$\nabla\cdot\vec{q} = \nabla\cdot\vec{q}_\perp + \nabla\cdot\vec{q}_{//} = 0 \qquad \nabla\cdot\vec{q}_{//} = q_{//t}/L \qquad \tau_{//} = \frac{3nTL}{q_{//t}}$$

$$2n\chi_\perp \frac{d^2T}{dr^2} = \frac{3nT}{\tau_{//}} \longrightarrow T = T_s\exp(-r/\lambda_p) \qquad \lambda_p = (\chi_\perp\tau_{//}/3)^{1/2}$$

using $q_{\perp s} = -n_s\chi_\perp dT/dr$

$$\lambda_p = \chi_\perp n_s T_s / q_{\perp s}$$

$$q_{//t} = \frac{q_{\perp s}^2 L}{\chi_\perp n_s T_s}$$

setting $T_s = T_u \quad q_{//t} = q_{//}$

when $T_u^{7/2} >> T_t^{7/2}$

$$T_u = \left(\frac{7q_{//}L}{2\alpha}\right)^{2/7}$$

$$\lambda_p[m] = 5.0\times10^{-16}\frac{L^{4/9}(\chi_\perp n_s)^{7/9}}{q_{\perp s}^{5/9}}$$

for $q_{\perp s}[MWm^{-2}] = 0.5 \quad L[m] = 150$

$\chi_\perp[m^2s^{-1}] = 1 \quad n_u[m^{-3}] = 1\times10^{20}$

$$q_{//t}[Wm^{-2}] = 2.0\times10^{15}\frac{L^{5/9}q_{\perp s}^{14/9}}{(\chi_\perp n_s)^{7/9}}$$

$\longrightarrow \quad \lambda_p[m] = 0.01 \quad q_{//t}[Wm^{-2}] = 7\times10^9$

Poloidal heat flux $\quad q_{pol}[Wm^{-2}] \sim (B_p/B_\phi)q_{//t}[Wm^{-2}] \sim 10^8 >> 5\times10^6$

Volume Losses of Power in the Divertor

To minimize power deposition on the target plates, radiate power so that it can be distributed over a large surface area

- **Introduce impurity to enhance the radiation,** $P_r = \int n_m n_e R(T_e) dV$

  maximum radiation parameter, $R(T_e) \sim 10^{-31} Wm^3$,

  for 1GW radiated power, $n_m n_e V < 10^{40} m^{-3}$

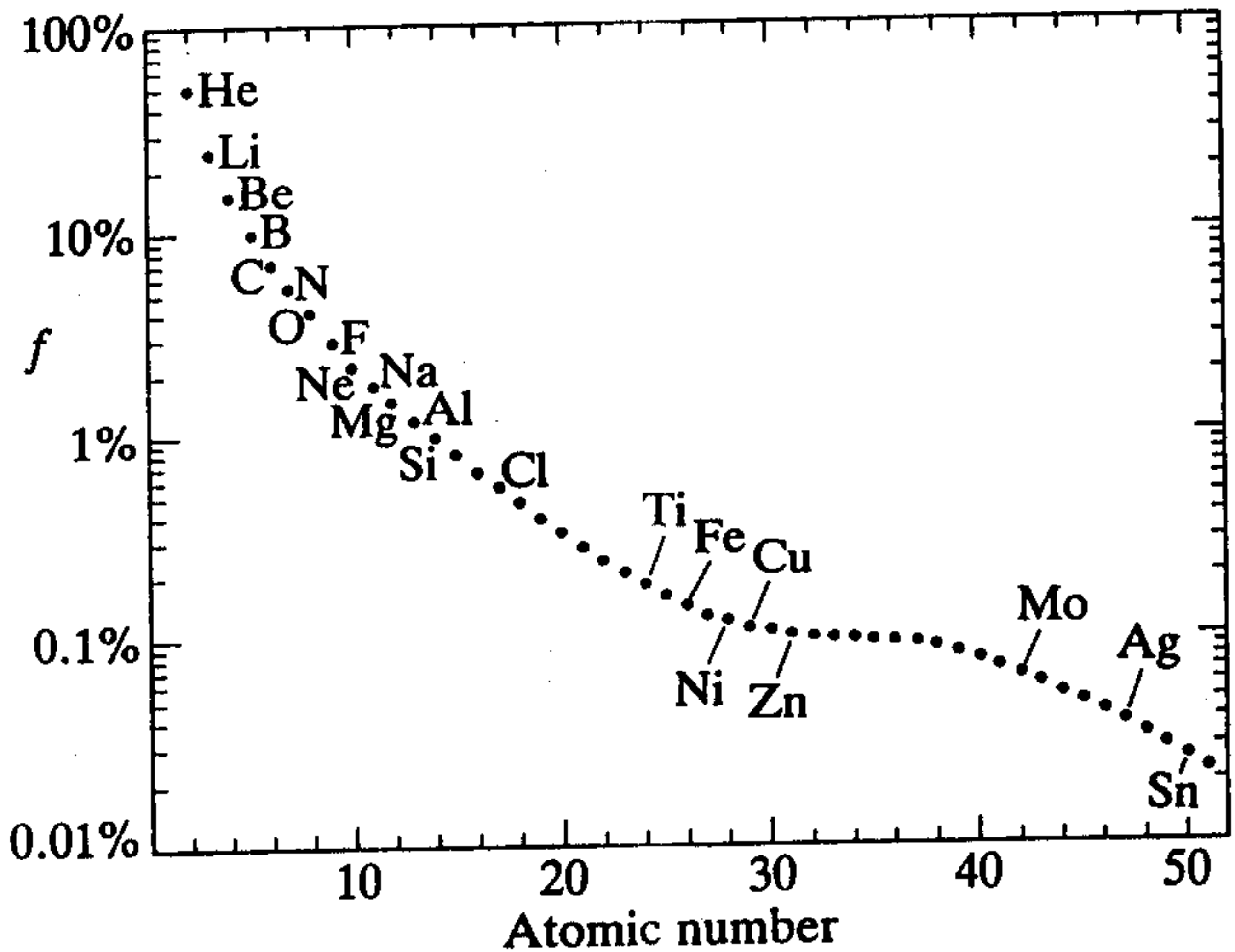
  ⟶ $n_m / n_e \sim 10\%$ with $n_e \sim 10^{20} m^{-3}$ and $V = 10 m^3$

  ⟶ Lead to impurities flowing into the confined plasma
  Cause unacceptable increase in the target sputtering

- **Volume loss mechanisms with charge exchange neutral loss (low plasma temp.) and ion-neutral collisions (high neutral density)**

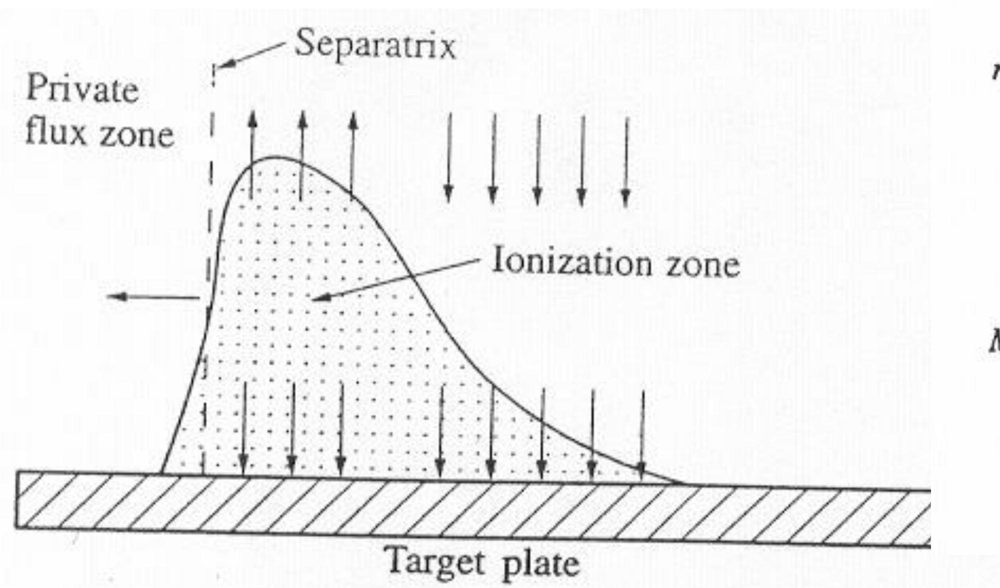
- **Detached divertor plasma :** momentum and energy must be transferred from the plasma to a neutral gas blanket near the target
  Detached plasma drops target density --> difficult helium ash removal

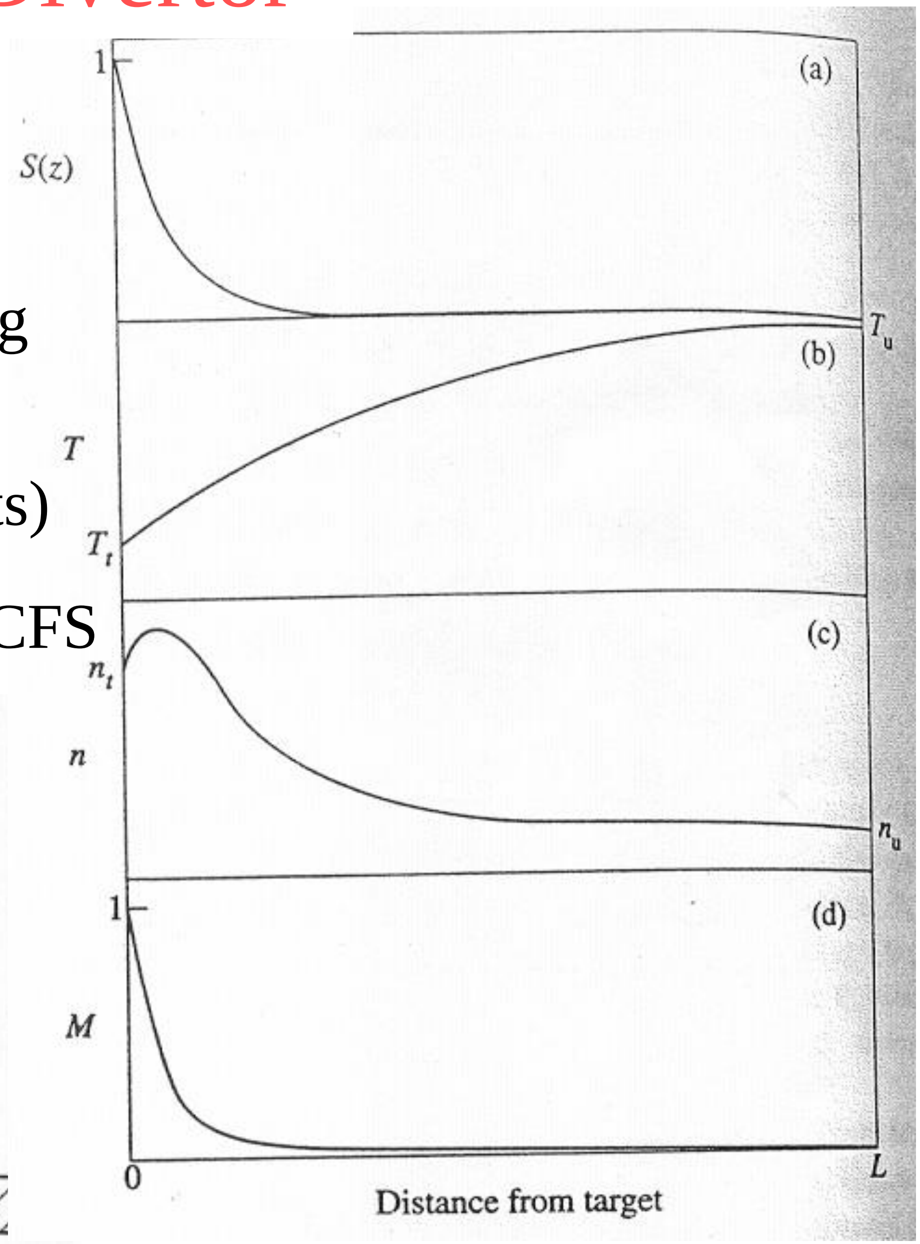
Allowable Fraction of Impurities



Flow in the Divertor

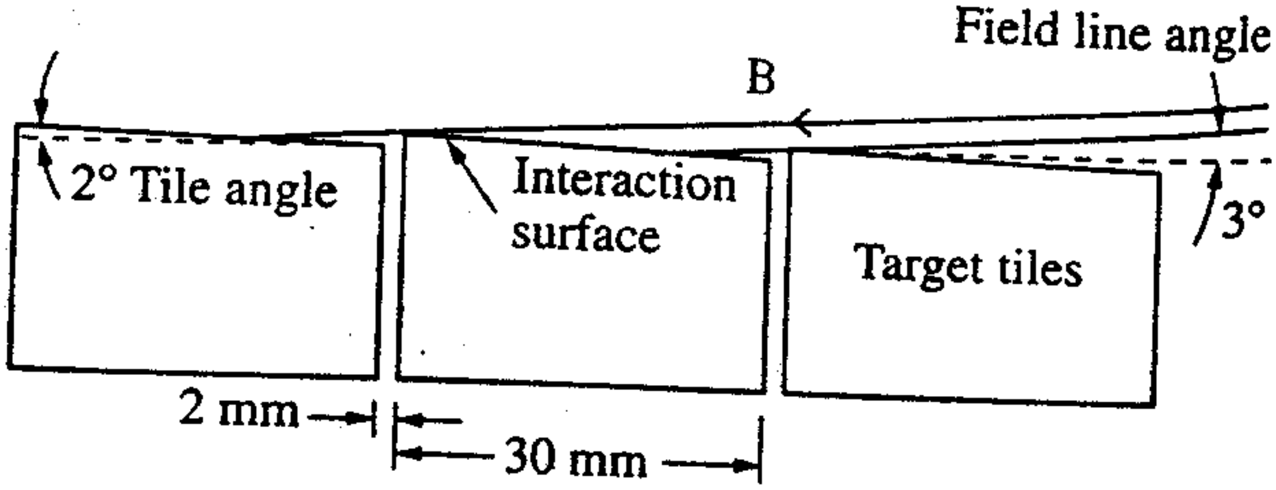
• Ionization due to recycling is localized near the target --> density peaks and temperature falls
• Helium ash removal requires very high pumping speed --> transporting the plasma to the separate divertor chamber can ease the restrictions (central fueling with NBI and pellets)
• High ionization due to high local density --> reverse flows back to LCFS





General Design Considerations for the Divertor

- Single and Double nulls
  - double null doubles wall interaction area and halves connection length, more triangularity, decreases plasma volume
- Target geometries: flat plates and enclosed chamber
  - flat plates: simple, easy diagnostic access, rigid structure
  - enclosed chamber: good isolation from the main confined plasma
- Target tiles
  - reduce thermal stress due to non-uniform heat flux --> make small
  - increase the effective area with small angle, and displace targets
- Erosion of the surface and consequent redeposition of eroded material



Tritium Behavior

Diffusion-dominated hydrogen distribution

- implanted tritium moves both by diffusion and surface recombination

- release rate for diffusion dominant case with uniform distribution $R = At^{-1/2}$

- non-metalic material : porous, pearmeate and trapped at the lattice defects
  --> heating and hydrogen discharge can remove tritium

- Wall materials(exothermically dissolving hydrogen, Ti, Zr, Nb) release little gas and build up tritium inventory --> not tolerable