Appendix A

A.1 Some Important Relations and Parameters

Stefan–Boltzmann Law:

$$E = \sigma_{\mathrm{SB}} T^4$$
$$\sigma_{\mathrm{SB}} = \frac{2\pi^5 k_{\mathrm{B}}^4}{15c^2h^3} = \frac{C_1}{15}\left(\frac{\pi}{C_2}\right)^4 = 5.668\times 10^{-8}\left[\frac{\mathrm{W}}{\mathrm{m^2K^4}}\right] \tag{A.1}$$

where $C_1 = 3.7418 \times 10^{-16}\,\mathrm{Wm^2}$ and $C_2 = 1.4388 \times 10^{-2}\,\mathrm{mK}$.

Thermal Diffusivity:

$$a = \frac{k}{\rho \cdot c_{\mathrm{p}}}\left[\frac{\mathrm{m^2}}{\mathrm{s}}\right] \tag{A.2}$$

with $[k]$=W/(mK), $[c_{\mathrm{p}}]$=J/(kgK), and $[\rho]$=kg/m^3.

Coefficient ζ:

$$\zeta = \frac{2}{\sqrt{\pi\,\rho\,c_{\mathrm{p}}\,k}}\left[\frac{\mathrm{Km^2}}{\mathrm{Ws^{1/2}}}\right] \tag{A.3}$$

used in

$$T_{\mathrm{s}} = T_{\mathrm{so}} + P\,\zeta\,\sqrt{t} \tag{A.4}$$

to calculate the rise of surface temperature due to a heat load of $P\,[\mathrm{W/m^2}]$ onto a half-infinite solid during the time t. T_{o} is the initial surface temperature at $t = 0$. For most materials, $\zeta \simeq (0.5–1.0)\times 10^{-4}$ in a wide range of surface temperatures.

Electron Plasma Frequency:

$$\omega_{\rm pe} = \sqrt{\frac{n_{\rm e} e^2}{m_{\rm e} \epsilon_{\rm o}}} \ \text{[rad/s]} \tag{A.5}$$

Ion Plasma Frequency:

$$\omega_{\rm pi} = \sqrt{\frac{n_{\rm i} q^2 e^2}{m_{\rm i} \epsilon_{\rm o}}} \ \text{[rad/s]} \tag{A.6}$$

Debye Length:

$$\lambda_{\rm D} = \sqrt{\frac{\epsilon_{\rm o} k_{\rm B} T}{n_{\rm e} e^2}} \ \text{[m]} \tag{A.7}$$

Number of Particles Inside a Debye Sphere:

$$N_{\rm D} = \frac{4}{3} \pi \lambda_{\rm D}^3 n_{\rm pl} = \frac{4\pi}{3} \left(\frac{\epsilon_{\rm o} k_{\rm B} T}{n_{pl}^{1/3} e^2} \right)^{3/2} \ \text{[particles]} \tag{A.8}$$

Electron Cyclotron Frequency:

$$\omega_{\rm ce} = \frac{eB}{m_{\rm e}} \ \text{[rad/s]} \tag{A.9}$$

Ion Cyclotron Frequency:

$$\omega_{\rm ci} = \frac{qeB}{m_{\rm i}} \ \text{[rad/s]} \tag{A.10}$$

Electron Gyro-Radius:

$$\rho_{\rm ce} = \frac{v_{\perp \rm e}}{\omega_{\rm ce}} = \frac{m_{\rm e} v_{\perp \rm e}}{eB} \ \text{[m]} \tag{A.11}$$

Ion Gyro-Radius:

$$\rho_{\mathrm{ci}} = \frac{v_{\perp \mathrm{i}}}{\omega_{\mathrm{ci}}} = \frac{m_{\mathrm{i}} v_{\perp \mathrm{i}}}{qeB} \ [\mathrm{m}] \tag{A.12}$$

Redeposition Parameter:

$$\gamma_p = \frac{\lambda_{\mathrm{iz}}}{\rho} \frac{v_{\perp \mathrm{i}}}{\omega_{ci}} = \frac{m_{\mathrm{i}} v_{\perp \mathrm{i}}}{qeB} \ [\mathrm{m}] \tag{A.13}$$

Magnetization Parameter (Dielectric Susceptibility):

$$\xi_{\mathrm{e,i}} = \frac{\rho_{\mathrm{e,i}}^2}{\lambda_{\mathrm{D}}^2} = \frac{n_{\mathrm{pl}} m_{\mathrm{e,i}}}{\epsilon_{\mathrm{o}} B^2} \tag{A.14}$$

Ion Sound Speed:

$$c_{\mathrm{s}} = \sqrt{\frac{\gamma_{\mathrm{e}} k_{\mathrm{B}} T_{\mathrm{e}} + \gamma_{\mathrm{i}} k_{\mathrm{B}} T_{\mathrm{i}}}{m_{\mathrm{i}}}} \ [\mathrm{m/s}] \tag{A.15}$$

where γ_{i} can be set equal to 3, since ions are subjected to one-dimensional compression, whereas electrons are fast enough to reach thermal equilibrium so that $\gamma_{\mathrm{e}} = 1$. The sound speed depends on the electron temperature, since the arising electric field is proportional to this temperature and ion mass, due to the inertia of the fluid.

Particle Drifts:

In an electric field:

$$\boldsymbol{v}_{\mathrm{E}} = (\boldsymbol{E} \times \boldsymbol{B})/B^2 \ [\mathrm{m/s}] \tag{A.16}$$

In gravity:

$$\boldsymbol{v}_{\mathrm{g}} = m(\boldsymbol{g} \times \boldsymbol{B})/(qB^2) \ [\mathrm{m/s}] \tag{A.17}$$

Due to a force $\boldsymbol{F}$:

$$\boldsymbol{v}_{\mathrm{F}} = (\boldsymbol{F} \times \boldsymbol{B})/(qB^2) \ [\mathrm{m/s}] \tag{A.18}$$

Due to a gradient of $\boldsymbol{B}$:

$$\boldsymbol{v}_{\mathrm{G}} = -\frac{m v_{\perp}^2}{2qB} \frac{(\boldsymbol{\nabla} B) \times \boldsymbol{B}}{B^2} \ [\mathrm{m/s}] \tag{A.19}$$

Due to curvature of $\boldsymbol{B}$:

$$\boldsymbol{v}_{\mathrm{C}} = -\frac{mv_\parallel^2}{qB^3}\left[(\boldsymbol{B}\cdot\boldsymbol{\nabla})\frac{\boldsymbol{B}}{B}\right]\times\boldsymbol{B}\ [\mathrm{m/s}] \tag{A.20}$$

Due to polarization:

$$\boldsymbol{v}_{\mathrm{p}} = m\frac{\partial\boldsymbol{E}_\perp/\partial t}{qB^2}\ [\mathrm{m/s}] \tag{A.21}$$

Maxwellian Distribution:

The thermodynamical definition of temperature T is

$$3k_{\mathrm{B}}T/2 = m\langle v^2\rangle/2 = \frac{m}{2}\int_v f(v)\,v^2\,\mathrm{d}^3v\ . \tag{A.22}$$

The number of particles having a velocity in the interval $[v, v+\mathrm{d}v]$ is

$$nf(v)\mathrm{d}^3v = n\left(\frac{m}{2\pi k_{\mathrm{B}}T}\right)^{(3/2)}\exp\left(-\frac{mv^2}{2k_{\mathrm{B}}T}\right)\mathrm{d}^3v \tag{A.23}$$

where n is the particle density.

The one-dimensional distribution is given by

$$\begin{aligned} g(v_x)\mathrm{d}v_x = &\left(\frac{m}{2\pi k_{\mathrm{B}}T}\right)^{3/2}\exp\left(-\frac{mv_x^2}{2k_{\mathrm{B}}T}\right)\mathrm{d}v_x \\ &\times\int_{-\infty}^{+\infty}\exp\left(-\frac{mv_y^2}{2k_{\mathrm{B}}T}\right)\mathrm{d}v_y\int_{-\infty}^{+\infty}\exp\left(-\frac{mv_z^2}{2k_{\mathrm{B}}T}\right)\mathrm{d}v_z\ . \end{aligned} \tag{A.24}$$

Since each integral equals $(2\pi \mathrm{k}T/m)^{1/2}$ one obtains

$$g(v_x)\mathrm{d}v_x = \left(\frac{m}{2\pi k_{\mathrm{B}}T}\right)^{1/2}\exp\left(-\frac{mv_x^2}{2k_{\mathrm{B}}T}\right)\mathrm{d}v_x \tag{A.25}$$

with $\int_{-\infty}^{+\infty} g(v_x)\mathrm{d}v_x = 1$. The same relation is valid for $g(v_y)$ and $g(v_z)$.

The variance is given by

$$\langle v_i^2\rangle = \int_{-\infty}^{+\infty} g(v_i)v_i^2\mathrm{d}v_i = \frac{k_{\mathrm{B}}T}{m} \tag{A.26}$$

resulting in $\sqrt{\langle v_i^2\rangle} = \sqrt{k_{\mathrm{B}}T/m}$ and $m\langle v_i^2\rangle/2 = k_{\mathrm{B}}T/2$. The velocity components are statistically independent on each other, i.e.,

$$f(\boldsymbol{v})\mathrm{d}\boldsymbol{v} = g(v_x)\mathrm{d}v_x\cdot g(v_y)\mathrm{d}v_y\cdot g(v_y)\mathrm{d}v_y\ . \tag{A.27}$$

The velocity distribution as a function of $v = |\boldsymbol{v}|$ is

$$F(v)\mathrm{d}v = \int_{\theta}\int_{\varphi} f(v)v^2 \sin\theta \mathrm{d}\theta \mathrm{d}\varphi \mathrm{d}v = 4\pi v^2 f(v)\mathrm{d}v \tag{A.28}$$

since $\mathrm{d}^3v = v^2 \sin\theta \mathrm{d}\theta \mathrm{d}\varphi \mathrm{d}v$ and $4\pi v^2 \mathrm{d}v$ represents the volume of a sphere in the velocity space

$$F(v) = 4\pi \left(\frac{m}{2\pi \mathrm{k}T}\right)^{(3/2)} v^2 \exp\left(-\frac{mv^2}{2\mathrm{k}T}\right) . \tag{A.29}$$

The average velocity is shown to be

$$\langle v \rangle = \int \int_{-\infty}^{+\infty} \int f(v)\, v\, \mathrm{d}v_x \mathrm{d}v_y \mathrm{d}v_z = \int_0^{+\infty} F(v)\, v\, \mathrm{d}v = \left(\frac{8k_{\mathrm{B}}T}{\pi m}\right)^{1/2} . \tag{A.30}$$

The average square velocity is given by

$$\langle v^2 \rangle = \int_0^{+\infty} F(v) v^2 \,\mathrm{d}v = 3k_{\mathrm{B}}T/m . \tag{A.31}$$

The most probable velocity is then

$$v_{\mathrm{mp}} = \sqrt{2k_{\mathrm{B}}T/m} \tag{A.32}$$

satisfying the condition

$$\left.\frac{\mathrm{d}F(v)}{\mathrm{d}v}\right|_{v_{\mathrm{mp}}} = 0 . \tag{A.33}$$

The energy distribution ($E = mv^2/2$) can be presented as

$$g(E)\mathrm{d}E = \frac{2}{\sqrt{\pi}} \left(\frac{E}{(k_{\mathrm{B}}T)^3}\right)^{1/2} \exp\left(-\frac{E}{k_{\mathrm{B}}T}\right) \mathrm{d}E . \tag{A.34}$$

The particle flux density is given as

$$\begin{aligned} \mathit{\Gamma}_z &= n \int_0^{\infty} f(v) v^3 \mathrm{d}v \int_0^{\pi/2} \sin\theta \cos\theta \,\mathrm{d}\theta \int_0^{2\pi} \mathrm{d}\varphi = n\,\pi \int_0^{\infty} f(v) v^3 \mathrm{d}v \\ &= n(k_{\mathrm{B}}T/(2\pi m))^{1/2} = n\langle v \rangle/4 . \end{aligned} \tag{A.35}$$

Other often used distributions are

$$f(v = \sqrt{v_x^2 + v_y^2 + v_z^2})$$

$$= 4\pi \left(\frac{m}{2\pi k_\mathrm{B} T}\right)^{(3/2)} v^2 \exp\left(-\frac{mv^2}{2k_\mathrm{B}T}\right) \rightarrow \langle v \rangle = \sqrt{\frac{8k_\mathrm{B}T}{\pi m}} \quad \text{(A.36)}$$

$$f(v = \sqrt{v_x^2 + v_y^2}) = \left(\frac{m}{k_\mathrm{B} T}\right) v \exp\left(-\frac{mv^2}{2k_\mathrm{B}T}\right) \rightarrow \langle v \rangle = \sqrt{\frac{\pi k_\mathrm{B}T}{2m}} \quad \text{(A.37)}$$

$$f(v = |v_x|) = 2 \left(\frac{m}{2\pi k_\mathrm{B} T}\right)^{1/2} \exp\left(-\frac{mv^2}{2k_\mathrm{B}T}\right) \rightarrow \langle v \rangle = \sqrt{\frac{2k_\mathrm{B}T}{\pi m}} \quad \text{(A.38)}$$

with $\int_0^\infty v f(v) \mathrm{d}v = \langle v \rangle$.

Collision Frequencies:

The collision frequency for momentum transfer between a test particle a and field particles b with their charges q_a, q_b, their masses m_a, m_b, and their thermal velocities $v_{\mathrm{th},a}$, $v_{\mathrm{th},b}$, respectively, is given by

$$\nu_{ab} = \frac{16\sqrt{\pi}}{3m_a} \left(\frac{1}{m_a} + \frac{1}{m_b}\right) \frac{q_a^2 q_b^2 e^4 n_b \ln \Lambda}{(4\pi\epsilon_\mathrm{o})^2 (v_{\mathrm{th},a}^2 + v_{\mathrm{th},b}^2)^{3/2}} \,. \quad \text{(A.39)}$$

For electron and singly charge ions ($q_\mathrm{e} = -1, q_\mathrm{i} = 1$) the collision frequencies are

$$\nu_\mathrm{ii} = \frac{1}{(4\pi\epsilon_\mathrm{o})^2} \frac{4}{3} \frac{\sqrt{\pi}\, e^4\, n_\mathrm{i} \ln \Lambda}{\sqrt{m_\mathrm{i}}\, (k_\mathrm{B} T_\mathrm{i})^{3/2}} \quad \text{(A.40)}$$

$$\nu_\mathrm{ee} = \frac{1}{(4\pi\epsilon_\mathrm{o})^2} \frac{4}{3} \frac{\sqrt{\pi}\, e^4\, n_\mathrm{e} \ln \Lambda}{\sqrt{m_\mathrm{e}}\, (k_\mathrm{B} T_\mathrm{e})^{3/2}} \quad \text{(A.41)}$$

$$\nu_\mathrm{ei} = \frac{1}{(4\pi\epsilon_\mathrm{o})^2} \frac{4}{3} \frac{\sqrt{2\pi}\, e^4\, n_\mathrm{i} \ln \Lambda}{\sqrt{m_\mathrm{e}}\, (k_\mathrm{B} T_\mathrm{e})^{3/2}} \quad \text{(A.42)}$$

$$\nu_\mathrm{ie} = \frac{1}{(4\pi\epsilon_\mathrm{o})^2} \frac{4}{3} \frac{\sqrt{2\pi m_\mathrm{e}}\, e^4\, n_\mathrm{e} \ln \Lambda}{m_\mathrm{i}\, (k_\mathrm{B} T_\mathrm{e})^{3/2}} \quad \text{(A.43)}$$

where $\nu_\mathrm{ie} = (m_\mathrm{e}/m_\mathrm{i})\, \nu_\mathrm{ei}$, $\nu_\mathrm{ii} = \nu_\mathrm{ee} \sqrt{m_\mathrm{e}/m_\mathrm{i}}$, and $\nu_\mathrm{ei} = \sqrt{2}\, \nu_\mathrm{ee}$.

A.2 Simple Particle Mover

The equation of motion (9.99) is given in Cartesian coordinates by

$$\begin{aligned} M\frac{\mathrm{d}v_x}{\mathrm{d}t} &= qE_x + Qv_yB_z - Qv_zB_y \qquad (A.44)\\ M\frac{\mathrm{d}v_y}{\mathrm{d}t} &= qE_y - Qv_xB_z + Qv_zB_x \\ M\frac{\mathrm{d}v_z}{\mathrm{d}t} &= qE_z + Qv_xB_y - Qv_yB_x \end{aligned}$$

with the components of the electric field $\boldsymbol{E} = (E_x, E_y, E_z)$ and the magnetic field $\boldsymbol{B} = (B_x, B_y, B_z)$. Using an implicit scheme of second order accuracy [547] in substituting the derivatives by differences yields

$$\frac{\mathrm{d}v_\mathrm{i}}{\mathrm{d}t} = \frac{v_\mathrm{i}^{n+1} - v_\mathrm{i}^n}{\Delta t} \quad \text{and} \quad v_\mathrm{i} = \frac{v_\mathrm{i}^{n+1} + v_\mathrm{i}^n}{2}$$

for $i = (x, y, z)$. This scheme conserves the kinetic energy. The index n denotes the steps in time. The system of equations (A.44) can be expressed in matrix notation

$$\begin{pmatrix} 1 & -C\,B_z & C\,B_y \\ C\,B_z & 1 & -C\,B_x \\ -C\,B_y & C\,B_x & 1 \end{pmatrix} \begin{pmatrix} v_x^{n+1} \\ v_y^{n+1} \\ v_z^{n+1} \end{pmatrix} = \begin{pmatrix} v_x^n + 2C\,E_x + C\,B_z v_y^n - C\,B_y v_z^n = s_1 \\ v_y^n + 2C\,E_y - C\,B_z v_x^n + C\,B_x v_z^n = s_2 \\ v_z^n + 2C\,E_z + C\,B_y v_x^n - C\,B_x v_y^n = s_3 \end{pmatrix}$$

with $C = Q\Delta t/(2M)$, where Q is the charge and M is the mass of the particle. The corresponding determinant is

$$\Delta = 1 + C^2(B_x^2 + B_y^2 + B_z^2) = 1 + C^2B^2\ . \qquad (A.45)$$

The new components for the velocity after time step Δt are given by

$$\begin{aligned} v_x^{n+1} &= \frac{s_1(1 + C^2B_x^2) + s_2(C\,B_z + C^2B_xB_y) + s_3(C^2B_xB_z - C\,B_y)}{1 + C^2B^2} \\ v_y^{n+1} &= \frac{s_1(C^2B_xB_y - C\,B_z) + s_2(1 + C^2B_y^2) + s_3(C\,B_x + C^2B_zB_y)}{1 + C^2B^2} \\ v_z^{n+1} &= \frac{s_1(C^2B_zB_x + C\,B_y) + s_2(C^2B_yB_z - C\,B_x) + s_3(1 + C^2B_z^2)}{1 + C^2B^2}\ . \end{aligned}$$

The new positions are calculated as follows:

$$\begin{aligned} x^{n+1} &= x^n + (v_x^{n+1} + v_x^n)\Delta t/2 \\ y^{n+1} &= y^n + (v_y^{n+1} + v_y^n)\Delta t/2 \\ z^{n+1} &= z^n + (v_z^{n+1} + v_z^n)\Delta t/2\ . \qquad (A.46) \end{aligned}$$

An appropriate choice of the time step is necessary in order to reduce numerical errors.

A.3 Symbols

An attempt has been made to avoid double denotation of symbols throughout the text. For this purpose, it has been necessary to add subscripts in the case of commonly used symbols for certain physical parameters. The use of remaining double denotations (e.g., E for energy and electric field, ρ for gyro-radius and density) hopefully becomes clear from the context. The usage of Z for atomic numbers (nuclear charges) in solid state physics as well as for charge states in plasma physics especially leads to some confusion. In the following text, Z is used to denote atomic numbers, q is the charge state, and $Q = qe$ is the charge.

The following subscripts have been used more frequently: (e) electron, (eff) effective, (E) energy, (i) ion, (imp) impurity, (o) initial condition, (pl) plasma, (q) charge state, ($\perp$) perpendicular, ($\|$) parallel.

a	Thermal diffusivity
a_{t}	Minor radius in toroidal geometry
a_{L}	Lindhard screening length
a_{o}	Bohr radius
a_{s}	Screening length
A	Mass number in [amu]
$A_{k\to i}$	Transition probability
B	Magnetic field
c	Speed of light in vacuum
c_{A}, c_{B}	Concentration of species A and B
c_{br}	Bremsstrahlung coefficient
c_{p}	Heat capacity at constant pressure
c_{s}	Ion sound speed
C	Coefficient
C_{d}	Fitting parameter
d	Thickness
d_{m}	Dimension
D_{B}	Bohm diffusion coefficient
D	Diffusion coefficient
$D_{\perp}$	Cross-field diffusion coefficient
e	Elementary charge
E	Energy
E	Electric field
$E_{\|}$	Electric field parallel to $\boldsymbol{B}$
$E_{\perp}$	Electric field perpendicular to $\boldsymbol{B}$
E_{em}	Energy of emitted electrons
E_{F}	Fermi energy
E_{i}	Ion energy at sheath entrance
E_{s}	Heat of sublimation
E_{th}	Threshold energy for sputtering

E_{therm}	Thermal energy
E_{TF}	Thomas–Fermi energy
E_{Y}	Young modulus
E_{α}	Helium energy
f	Fraction of particles
f_{esc}	Escape probability
f_{G}	Gamov factor
f_{i}	Impurity concentration
f_{P}	Probability
f_{y}	Yamamura parameter
$f(v)$	Velocity distribution
$f(\boldsymbol{r}, \boldsymbol{v}, t)$	Distribution function in phase space
F	Force
F_{R}	Friction force
$F(v)$	Velocity distribution
g	Standard acceleration of gravity
g_{T}	Troyan factor
$g(v)$	Velocity distribution
$g(E)$	Energy distribution
G	Deposition distribution
h	Planck constant
i	Index
I	Electric current
I_{ion}	Ionization energy
I_{p}	Plasma current
j	Electric current density
j_{ce}	Electron emission current density
j_{e}	Electron current density
j_{i}	Ion current density
j_{s}	Thermionic current density
k	Heat conductivity
k_{B}	Boltzmann constant
k_{L}	Lindhard–Scharff coefficient
l	Length
l_{p}	Mean free path
l_{tr}	Transport length
L	Lagrange function
L_{c}	Connection length of wall elements
L_{i}	Impurity radiation function
L_{z}	Cooling rate for certain impurity and charge state
m	Mass
m_{e}	Electron mass
m_{i}	Ion mass
m_{p}	Exponent of the power potential
M_{1}	Mass of incident particle

M_2	Mass of target atom
M_φ	Angular momentum
n	Particle density
n_o	Atomic density in solids
n_e	Electron density
n_{pl}	Plasma density
n_q	Density of plasma impurities of charge state q
n_s	Surface concentration in particles/m^2
N	Number of particles
N_D	Number of particles in a Debye sphere
N_F	Number of Frenkel pairs
N_t	Number of scattering centers
N_Z	Number of quantum states
p	Pressure
p_x, p_y, p_z	Components of the momentum
P	Heat flux density
P_{alpha}	Helium fusion power
P_{brems}	Bremsstrahlung losses
P_e	Electron heat flux density
P_i	Ion heat flux density
P_{pr}	Probability of prompt redeposition
P_q	Radiation losses for a certain charge state
P_{redep}	Probability of redeposition
P_v	Power loss density
P_w	Total heat flux density
Pe	Peclet number
P_{rad}	Radiation power
q	Charge state of plasma particles
q_i	Charge state of impurity ions
q_s	Safety factor
Q	Charge
Q_t	Total charge
Q_E	Inner heat source
Q_{RES}	Fitting parameter for RES calculation
Q_y	Fitting parameter
r	Radius
r_o	Gas-kinetic radius
r_ρ	Normalized range
R	Reflection coefficient
R_{cyc}	Recycling coefficient
R_d	Depth
R_E	Energy reflection coefficient
R_N	Particle reflection coefficient
R_o	Total range

R_t	Major radius in toroidal geometry
$R(z)$	Depth distribution
s	Sticking coefficient
s_n	Nuclear stopping cross-section
S	Surface area
S_n	Stopping cross-section
S_q	Ionization rate coefficient
S_{wall}	Area of wall elements
t	Time
t_c	Self-collision time
t_d	Deflection time
t_{exp}	Exposure time
t_E	Energy exchange time
t_{pl}	Plasma oscillation time
t_s	Slowing down time
T	Temperature
T_e	Electron temperature
T_i	Ion temperature
T_m	Melting temperature
T_s	Surface temperature
u	Velocity in the center-of-mass system
U	Potential energy
U_o	Energy of a motionless electron in vacuum
$U(r)$	Interaction potential
v	Velocity
v_A	Alvén velocity
v_B	Bohr velocity
v_c	Velocity of the center of mass
v^s	Recession/deposition speed
$v_\parallel$	Parallel velocity
$v_\perp$	Transverse velocity
V	Volume
W_E	Plasma energy content
W_{th}	Thermal energy
W_T	Thermionic work function
x	Cartesian x-coordinate, length
y	Cartesian y-coordinate
Y	Sputtering yield
Y_{eff}	Effective sputtering yield
z	Cartesian z-coordinate, depth
Z	Nuclear charges, atomic number
Z_1	Atomic number of incident particles
Z_2	Atomic number of bulk atoms
Z_{eff}	Effective charge state

α	Angle
α-particle	Helium
α_e	Coefficient of electron temperature gradient
α_i	Coefficient of ion temperature gradient
α_T	Thermal expansion coefficient
α_q	Recombination rate coefficient
β	Ratio of plasma to magnetic pressure
β^*	Critical β value
γ	Ratio of particle to energy confinement time
γ_B	Branching ratio
γ_G	Gaunt factor
γ_k	Kinematic factor
γ_i, γ_e	Ratio of the specific heats, c_p/c_V
γ_{ero}	Ratio of displacement to density decay length
γ_{imp}	Ratio of f_{imp} to f_{crit}
γ_E	Energy transmission factor
γ_p	Ratio of gyro-radius to ionization length
γ_{rad}	Ratio of radiation to input power
γ_{RE}	Generation rate of runaway electrons
γ_σ	Material stress parameter
$\mathit{\Gamma}$	Flux density
$\mathit{\Gamma}_{coupl}$	Coupling constant
δ	Emission coefficient
$\mathit{\Delta}$	Distance, displacement, thickness
Δ	Increment
ϵ_o	Permittivity of vacuum
ϵ	Exhaust efficiency
ε	Reduced energy
ε_g	Grayness coefficient
$\bar{\varepsilon}$	Average energy losses
ζ	Material constant
η	Resistivity
η_v	Viscosity
θ	Angle, poloidal angle
ι	Rotational transform
κ	Elongation
λ_D	Debye length
λ_{iz}	Ionization length
λ_n	Plasma density decay length
λ_{SOL}	Plasma decay length in the SOL
$\lambda_{n,l}$, $\lambda_{n,r}$	Plasma decay length in the divertor
Λ(T)	Integral thermal conductivity

$\ln \Lambda$	Coulomb logarithm
μ	Reduced mass
μ_b	Mobility
μ_o	Permeability of vacuum
ν	Collision frequency
ν_P	Poisson ratio
ξ	Magnetization parameter
ρ	Density, charge density
ρ_p	Collision parameter, impact parameter
ρ_{ce}	Electron gyro-radius
ρ_{ci}	Ion gyro-radius
σ	Cross-section
σ^*	Scattering parameter
σ^*_R	Backscattering parameter
σ_c	Plasma conductivity
σ_{SB}	Constant in Stefan–Boltzmann law
σ_{tr}	Transport cross section
σ_{ts}	Thermal stress
σ_y	Yield strength
$\langle \sigma v \rangle$	Rate coefficient
τ	Characteristic time
τ_p	Particle confinement time
τ_E	Energy confinement time
τ_{iz}	Ionization time
τ^*	Effective confinement time
φ	Angle, azimuthal angle
ϕ	Electric potential
ϕ_{fl}	Floating potential
ϕ_s	Potential at sheath entrance
ϕ_w	Wall potential
$\mathit{\Phi}$	Error function
$\mathit{\Phi}^o$	Particle flux
χ	Dielectric susceptibility
$\chi_\perp$	Anomalous energy transport coefficient
ω	Angular frequency
ω_{ce}	Electron cyclotron frequency
ω_{ci}	Ion cyclotron frequency
ω_{pe}	Electron plasma frequency
ω_{pi}	Ion plasma frequency
$\mathit{\Omega}$	Solid angle

A.4 Abbreviations

Alcator C-Mod	Tokamak at MIT, Boston (US) (*http://www.psfc.mit.edu/research/alcator*)
ASDEX-Upgrade	Axially Symmetric Divertor Experiment: tokamak at IPP, Garching (Germany) (*http://www.ipp.mpg.de/ippcms/eng/pr/forschung/asdex*)
A*THERMAL-S	Simulation code: time-dependent heat conduction [337]
B2-Eirene	Simulation code: 2D MHD coupled with a Monte Carlo transport code for neutrals [430]
CM-system	Center-of-mass system
CFC	Carbon fiber composites
CHS	Torsatron at NIFS, Nagoya (Japan): Compact Helical System (*http://rd-w3server.nifs.ac.jp/chs*)
CIC	Cloud-in-cell method
CPU	Central processing unit
CX	Charge exchange
dpa	Number of displacements per atom
DEMO	Name for a prototype fusion reactor demonstrating power production
DT	Deuterium–tritium mixture
ECR	Electron cyclotron resonance
ECRH	Electron cyclotron resonance heating: heating method using microwave radiation close to the resonance gyro-frequency of plasma electrons
EDA	Engineering design activities of ITER
ELM	Edge localized mode: relaxation instability of steep edge plasma profiles in the H-mode
erf	error function
ERO	Simulation code: erosion and impurity transport using Monte Carlo techniques [548]
ESS	European Spallation Source
ESEE	Electron impact secondary electron emission
FOREV	Simulation code: material erosion by large heat loads [338]
HEIGHTS	Simulation code: two-dimensional radiation–magnetohydrodynamic model [335]
high-Z	Materials such as molybdenum and tungsten with large atomic numbers
HL-1M	Tokamak at SWIP, Chengdu (China) (*http://www.swip.ac.cn*)
HT-7	Hefei Tokamak-7: superconducting tokamak at Institute of Plasma Physics, Hefei (China) (*http://english.cas.ac.cn*)
HTS	High-temperature superconductor
H-mode	Plasma regime of improved confinement characterized by steep gradients of the plasma parameters at the plasma edge

ICRF	Ion cyclotron resonance frequency
ICRH	Ion cyclotron resonance heating: heating method using radio frequencies close to the resonance gyro-frequency of plasma ions
IFMIF	International Fusion Materials Irradiation Facility
IPP	Max Planck Institute for Plasma Physics at Garching and Greifswald (Germany) (*http://www.ipp.mpg.de)*
ISEE	Ion impact secondary electron emission
ITB	Internal transport barrier
ITER	International Thermonuclear Experimental Reactor (ITER meaning "the way" in Latin): international project of a prototype fusion reactor based on the tokamak design (*http://www.iter.org*)
ITER–FEAT	Fusion Energy Advanced Tokamak
JET	Joint European Torus: up to now the world's largest tokamak experiment at Culham (UK) (*http://www.jet.efda.org*)
LHD	Large Helical Device: superconducting torsatron-type experiment at NIFS, Toki (Japan) (*http://www.lhd.nifs.ac.jp/en*)
LCFS	Last closed flux surface: boundary between the core plasma, where the magnetic field lines are closed, and the scrape-off layer
L-mode	The normal confinement mode in tokamaks
L-system	Laboratory system
low-Z	Materials such as beryllium, lithium and carbon with small atomic numbers
MARFE	Multi-faceted radiation from the edge: toroidally symmetric, but poloidally localized, radiation instability
MARLOWE	Simulation code: particle transport in crystal matter [271]
MC	Monte Carlo method: use of random numbers
MD	Molecular dynamics: many-particle interaction
MHD	Magnetohydrodynamics: theory of conducting fluids or plasmas in a magnetic field
NBI	Neutral beam injection for heating and refueling
NGP	Nearest grid point method
PKA	Primary knock-on atom
PIC	Particle-in-cell: kinetic simulation of plasmas with self-consistently obtained electromagnetic fields
PSI	Plasma surface interaction
PSI-1/2	Plasma generator: linear DC-arc discharge device at the Humboldt University, Berlin (Germany) (*http://plasma.physik.hu-berlin.de/psi/psi.html*)
Q-machine	Quiescent machine: generating plasmas with no electric field gradients and no instabilities by using thermionic electron emission and contact ionization for ion production

RBS	Rutherford backscattering technique for surface analysis
REDEP	Simulation code: erosion and redeposition [482]
RES	Radiation-enhanced sublimation
RND	Random number in the interval $[0, 1]$
Sawteeth	Periodic relaxation oscillations of the central plasma Parameters localized in a region roughly within the $q_\mathrm{s} = 1$ surface
SEE	Emission of secondary electrons
SKA	Secondary knock-on atom
SOL	Scrape-off layer: outer region of the plasma where the field lines intersect wall components (e.g., limiters or divertor plates)
TEXTOR	Tokamak Experiment for Technology Oriented Research: tokamak at IPP, Jülich (Germany) (*http://www.fz-juelich.de/ipp/textor*)
Tore-Supra	Superconducting tokamak at CEA, Cadarache (France) (*http://www-fusion-magnetique.cea.fr*)
TFTR	Tokamak Fusion Test Reactor: tokamak at PPPL, Princeton (US) (*http://www.pppl.gov/projects/pages/tftr.html*)
TRIM	Simulation code: particle transport in matter [266]
TRIM-SP	Simulation code: sputtering of solids and alloys [549]
TZM	Alloy of molybdenum with 0.5% Ti, 0.1% Zr
W7-X	New superconducting stellarator under construction at Greifswald (Germany) based on advanced design criteria (*http://www.ipp.mpg.de/ippcms/eng/pr/forschung/w7x*)
WBC	Simulation code: impurity transport in the plasma edge [424]
X-point	Point where two magnetic flux surfaces appear to cross (e.g., between magnetic islands or in the divertor region of tokamaks)

A.5 Fundamental Physical Constants

Table A.1. Physical constants used throughout the text

Constant, symbol	Value	Unit
Speed of light (vac.), c	2.99792458×10^{8}	m s^{-1}
Permittivity of vacuum, ϵ_o	$8.854187817 \times 10^{-12}$	C m^{-1}V^{-1}
Permeability of vacuum, μ_o	$4\pi \times 10^{-7}$	T m A^{-1}
Elementary charge, e	$1.602176462(63) \times 10^{-19}$	C
Electron mass, m_e	$9.10938188(72) \times 10^{-31}$	kg
Electron volt, eV	$1.602176462(63) \times 10^{-19}$	J
Proton mass, m_p	$1.67262158(13) \times 10^{-27}$	kg
Proton–electron mass ratio, m_p/m_e	1836.1526675(39)	1
Atomic mass unit, amu	$1.66053873(13) \times 10^{-27}$	kg
Boltzmann constant, k_B	$1.3806503(24) \times 10^{-23}$	J K^{-1}
Planck constant, h	$6.62606876(52) \times 10^{-34}$	J s
Planck constant over 2π, $\hbar = h/2\pi$	$1.054571596(82) \times 10^{-34}$	J s
Molar gas constant, R	8.314472(15)	J K^{-1} mol^{-1}
Avogadro constant, N_A	$6.02214199(47) \times 10^{23}$	mol^{-1}
Gravitational constant, G	$6.673(10) \times 10^{-11}$	m^3 kg^{-1} s^{-2}
Stefan–Boltzmann constant, σ	$5.670400(40) \times 10^{-8}$	W m^{-2} K^{-4}
Bohr radius, a_o	$5.291772083(19) \times 10^{-11}$	m
Classical electron radius, r_e	$2.817940285(31) \times 10^{-15}$	m
Fine-structure constant, α	$7.297352533(27) \times 10^{-3}$	
Inverse fine-structure constant, α^{-1}	137.03599976(50)	
Rydberg constant, R_∞	$1.0973731568549(83) \times 10^{7}$	m^{-1}
Electron magn. moment, μ_e	$-9.28476362(37) \times 10^{-24}$	J T^{-1}
Proton magn. moment, μ_p	$1.410606633(58) \times 10^{-26}$	J T^{-1}

The numbers in the brackets indicate the deviation of the last digit given, for example, 6.6260755(4) means 6.6260755 ± 0.0000004. These data are taken from the CODAS compilation [550, 551]. Additional information can be found in [552–555].

Table A.2. Important conversion factors

Length	Energy	Pressure
$1\,\mu m = 10^{-6}$ m	1 cal = 4.19 J	$1\,Pa = 9.87 \times 10^{-6}$ atm
$1\,nm = 10^{-9}$ m	$k=8.617 \times 10^{-5}$ eV/K	$1\,Pa = 10^{-5}$ bar
$1\,Å = 10^{-10}$ m	$1\,eV \equiv 11605$ K	$1\,Torr = 133.\bar{3}$ Pa
$1\,pm = 10^{-12}$ m	1 rydberg=13.61 eV	1 bar = 750 Torr

A.6 Physical Properties of Elements

In the following table a number of physical properties of elements up to uranium are summarized. They are

- Z: atomic number
- A: mass number
- n_o: atomic density, $n_o = \rho/(A \cdot \text{amu})$
- ρ: density
- c_p: heat capacity
- k: heat conductivity
- W: work function
- I_{ion}: ionization energy
- E_s: sublimation energy

The values given are valid for normal conditions and could serve for estimations and quick comparison. One should be aware of their particularly strong dependence on temperature and structure since some elements such as carbon are used to produce materials with apparently different properties, among them fine-grain graphite and carbon fiber composites (CFC).

Table A.3 Physical properties of elements

Z		A (amu)	$n_o, \times 10^{28}$ $(1/m^3)$	$\rho, \times 10^3$ (kg/m^3)	c_p (J/(kgK))	k (W/(mK))	W (eV)	I_{ion} (eV)	E_s (eV)
1	H	1.00794	–	–	–	–	–	13.6	–
2	He	4.0026	–	–	–	–	–	24.59	–
3	Li	6.941	4.633	0.534	3582	84.7	2.4	5.39	1.67
4	Be	9.01218	12.362	1.85	1825	200	3.9	9.32	3.38
5	B	10.811	12.929	2.32	–	–	4.5	8.3	5.73
6	C	12.0107	11.3	≈ 1.8	≈ 800	≈ 150	4.7	11.26	7.42
7	N	14.0067	–	–	–	–	–	14.53	–
8	O	15.9994	–	–	–	–	–	13.62	–
9	F	18.9984	–	–	–	–	–	17.42	–
10	Ne	20.1797	–	–	–	–	–	21.56	–
11	Na	22.9898	2.541	0.97	1228	141	2.3	5.14	–
12	Mg	24.3051	4.311	1.74	1023	156	3.6	7.65	–
13	Al	26.9815	6.026	2.7	897	237	4.2	5.99	3.36
14	Si	28.0855	–	–	–	–	4.8	8.15	4.7
15	P	30.9738	–	–	–	–	–	10.49	–
16	S	32.067	–	–	–	–	–	10.36	–
17	Cl	35.4527	–	–	–	–	–	12.97	–
18	Ar	39.948	–	–	–	–	–	15.76	–
19	K	39.0983	1.371	0.89	757	102.4	2.2	4.34	–
20	Ca	40.078	2.314	1.54	647	200	2.6	6.11	–
21	Sc	44.956	4.005	2.99	568	15.8	3.3	6.56	–
22	Ti	47.867	5.674	4.51	523	21.9	4.0	6.83	4.89
23	V	50.9415	7.093	6.0	489	30.7	4.1	6.75	5.33
24	Cr	51.9962	8.281	7.15	449	93.7	4.6	6.77	4.12
25	Mn	54.938	8.002	7.3	479	7.82	3.8	7.43	–
26	Fe	55.845	8.485	7.87	449	80.2	4.3	7.9	4.34
27	Co	58.9332	9.054	8.86	421	100	4.4	7.88	4.43
28	Ni	58.6934	9.132	8.9	444	90.7	4.5	7.64	4.46
29	Cu	63.546	8.491	8.96	385	401	4.5	7.73	3.52
30	Zn	65.39	6.576	7.14	388	116	4.2	9.39	–

Table A.3 continued

Z	A (amu)	$n_o, \times 10^{28}$ (1/m^3)	$\rho, \times 10^3$ (kg/m^3)	c_p (J/(kgK))	k (W/(mK))	W (eV)	I_{ion} (eV)	E_s (eV)
31 Ga	69.723	5.105	5.91	371	40.6	4.0	6.0	2.82
32 Ge	72.61	–	–	–	–	4.8	7.9	3.88
33 As	74.921	–	–	–	–	5.1	9.79	–
34 Se	78.96	–	–	–	–	4.7	9.75	–
35 Br	79.904	–	–	–	–	–	11.81	–
36 Kr	83.80	–	–	–	–	–	14.0	–
37 Rb	85.4678	1.078	1.53	363	58.2	2.2	4.18	–
38 Sr	87.62	1.814	2.64	301	35.3	2.3	5.69	–
39 Y	88.9059	3.028	4.47	298	17.2	3.3	6.22	–
40 Zr	91.224	4.304	6.52	278	22.7	3.9	6.63	6.33
41 Nb	92.9064	5.555	8.57	265	53.7	4.0	6.76	7.59
42 Mo	95.94	6.403	10.2	251	138	4.3	7.09	6.83
43 Tc	[98]	–	–	–	–	4.4	7.28	–
44 Ru	101.07	7.21	12.1	238	117	4.6	7.36	–
45 Rh	102.9055	7.257	12.4	243	150	4.7	7.46	–
46 Pd	106.42	6.791	12.0	246	71.8	4.8	8.34	3.91
47 Ag	107.8682	5.862	10.5	235	429	4.3	7.58	2.97
48 Cd	112.412	4.655	8.69	232	96.8	4.1	8.99	–
49 In	114.818	3.834	7.31	233	81.6	3.8	5.79	2.49
50 Sn	118.711	3.683	7.26	228	66.6	4.4	7.34	–
51 Sb	121.760	3.304	6.68	207	24.3	4.1	8.61	–
52 Te	127.60		–	–	–	4.7	9.01	–
53 I	126.9045	–	–	–	–	6.8	10.45	–
54 Xe	131.29	–	–	–	–	–	12.13	–
55 Cs	132.9054	0.875	1.93	242	35.9	1.8	3.89	–
56 Ba	137.327	1.587	3.62	204	18.4	2.5	5.21	–
57 La	138.906	2.666	6.15	195	13.4	3.3	5.58	–
58 Ce	140.116	2.91	6.77	192	11.3	2.7	5.54	–
59 Pr	140.908	2.893	6.77	193	12.5	2.7	5.46	–
60 Nd	144.24	2.927	7.01	190	16.5	3.2	5.52	–

Table A.3 continued

Z	A (amu)	n_o, $\times 10^{28}$ (1/m^3)	ρ, $\times 10^3$ (kg/m^3)	c_p (J/(kgK))	k (W/(mK))	W (eV)	I_{ion} (eV)	E_s (eV)
61 Pm	[145]	–	–	–	–	3.1	5.58	–
62 Sm	150.36	3.012	7.52	197	13.3	2.7	5.64	–
63 Eu	151.964	2.077	5.24	182	13.9	2.5	5.67	–
64 Gd	157.25	3.025	7.9	236	10.5	3.1	6.15	–
65 Tb	158.925	3.119	8.23	182	11.1	3.1	5.86	–
66 Dy	162.50	3.169	8.55	170	10.7	3.2	5.94	–
67 Ho	164.93	3.213	8.8	165	16.2	3.2	6.02	–
68 Er	167.26	3.266	9.07	168	14.5	3.2	6.11	–
69 Tm	168.934	3.322	9.32	160	16.9	3.1	6.18	–
70 Yb	173.04	2.401	6.9	155	38.5	2.6	6.25	–
71 Lu	174.967	3.387	9.84	154	16.4	3.1	5.43	–
72 Hf	178.49	4.487	13.3	144	23	3.5	6.83	–
73 Ta	180.948	5.458	16.4	140	57.5	4.1	7.55	–
74 W	183.84	6.322	19.3	132	174	4.5	7.86	8.68
75 Re	186.207	6.727	20.8	137	47.9	5.0	7.83	–
76 Os	190.23	7.151	22.59	130	87.6	4.7	8.44	–
77 Ir	192.217	7.049	22.5	131	147	4.7	8.97	–
78 Pt	195.078	6.637	21.5	133	71.6	5.3	8.96	5.86
79 Au	196.967	5.901	19.3	129	317	4.7	9.23	3.8
80 Hg	200.59	4.062	13.53	140	8.34	4.5	10.44	–
81 Tl	204.383	3.477	11.8	129	46.1	3.7	6.11	–
82 Pb	207.2	3.284	11.3	129	35.3	4.0	7.42	2.03
83 Bi	208.98	2.821	9.79	122	7.87	4.4	7.29	–
84 Po	[209]	2.651	9.2	–	–	4.7	8.42	–
85 At	[210]	–	–	–	–	–	–	–
86 Rn	[222]	–	–	–	–	–	10.75	–
87 Fr	[223]	–	–	–	–	1.6	4.07	–
88 Ra	[226]	1.332	5	–	–	3.2	5.28	–
89 Ac	[227]	2.653	10	–	–	2.7	5.17	–
90 Th	232.038	3.037	11.7	113	54	3.5	6.31	–
91 Pa	231.036	4.014	15.4	–	–	3.3	5.89	–
92 U	238.029	4.832	19.1	116	27.6	3.4	6.19	5.42

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