

Glossary

| Symbol | Definition | Equation | Section |
|-------------------------|--|----------|----------|
| a | minor radius of a torus | (3.53) | 3.6.3 |
| a | acceleration | (4.55) | 4.4.2.1 |
| a | radius of a dust particle | | 10.1.3.2 |
| a_{WS} | Wigner-Seitz radius | (2.16) | 2.1.3 |
| A_{br} | coefficient for bremsstrahlung | (4.64) | 4.4.2.3 |
| A_R | coefficient in Richardson's law | (11.10) | 11.1.5 |
| b | impact parameter | | 4.2.5 |
| b_c | impact parameter for charge collection | (10.5) | 10.1.3 |
| b_{90} | impact parameter for 90° deflection | (4.20) | 4.2.5 |
| B_{bc}, B_{cb} | Einstein coefficients | | 8.1.1 |
| B_m | maximum magnetic field in a mirror | | 3.4.2 |
| B_p | poloidal magnetic field | (3.55) | 3.6.1 |
| B_r | radial magnetic field | | 4.3.5 |
| B_t | toroidal magnetic field | (3.52) | 3.6 |
| B_{tot} | total magnetic mirror field | | 3.4.2 |
| \mathbf{B} | magnetic field vector | | 3.1 |
| $\hat{\mathbf{B}}$ | Fourier amplitude of \mathbf{B} | (6.8) | 6.1.2 |
| $b_{\pi/2}$ | impact parameter for 90° deflection | | 10.2.4 |
| C | capacitance of a dust particle | (10.10) | 10.1.3.2 |
| C_0 | capacitance of bulk plasma | (11.16) | 11.2.1 |
| C_L | sound speed of longitudinal mode | (10.93) | 10.4.1.5 |
| c_s | sound velocity | (6.79) | 6.5.3 |
| C_s | ion acoustic velocity | (6.78) | 6.5.3 |
| C_T | sound speed of transverse mode | | 10.4.1.5 |
| D | diffusion coefficient | (4.31) | 4.3.3 |
| D | Stix parameter | (6.90) | 6.6 |
| D | spring constant | (10.87) | 10.4.1.1 |
| $D(\omega, \mathbf{k})$ | dispersion function | (6.29) | 6.2 |
| D_a | ambipolar diffusion coefficient | (4.36) | 4.3.3.1 |

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|---------------------------|--|---------|----------|
| d_0 | equilibrium distance of dust particles | (10.68) | 10.2.5 |
| d_n | thickness of the normal cathode fall | (11.8) | 11.1.3 |
| $\hat{\mathbf{D}}_\omega$ | Fourier coefficient of displacement vector | (6.12) | 6.1.3 |
| E_a | ambipolar electric field | (4.37) | 4.3.3.1 |
| E_p | electric field at grid point p | (9.81) | 9.4.1 |
| \mathbf{E} | electric field vector | | 3.1 |
| $\hat{\mathbf{E}}$ | Fourier amplitude of \mathbf{E} | (6.8) | 6.1.2 |
| f_b | burn fraction of a pellet | (4.74) | 4.4.3.4 |
| F_c | collection force | (10.46) | 10.2.4 |
| F_{defl} | deflection force | | 8 |
| f_{e1} | perturbed electron distribution function | (9.35) | 9.3.1 |
| F_g | gravitational force on dust grain | | 10.2.1 |
| F_i | force on i -th particle | (9.82) | 9.4.1 |
| f_m | resonance frequencies of a cavity | (6.58) | 6.4.4 |
| F_i | ion wind force | (10.45) | 10.2.4 |
| f_M | Maxwell distribution, general | (2.10) | 2.1.1 |
| $f_M(v)$ | Maxwell distribution of speeds | (4.6) | 4.1 |
| $f_M(v_x)$ | shifted Maxwellian | (5.5) | 5.1.2 |
| $f_M^{(1)}$ | 1D Maxwell distribution | (4.1) | 4.1 |
| $f_M^{(3)}$ | 3D Maxwell distribution | (4.5) | 4.1 |
| $F_M(W)$ | Maxwell distribution of energies | (4.9) | 4.1.4 |
| \mathbf{F}_n | Epstein drag force | (10.41) | 10.2.2 |
| F_o | orbit force | (10.58) | 10.2.4 |
| F_p | ponderomotive force | (3.63) | 3.7.1 |
| F_{rest} | restoring force | | 8 |
| \mathbf{F}_{tp} | thermophoretic force | (10.43) | 10.2.3 |
| F_{trap} | force exerted by potential trap | (10.66) | 10.2.5 |
| F_Y | Yukawa interaction force | (10.64) | 10.2.5 |
| $f_+(x, v)$ | part of distribution function | (9.25) | 9.2.1 |
| $f_-(x, v)$ | part of distribution function | (9.27) | 9.2.1 |
| $F_{<}, F_{>}$ | force from inside and outside | (10.75) | 10.3.4 |
| g | gravitational acceleration on Earth | (10.32) | 10.2.1.1 |
| g_L | Lunar gravitational acceleration | | 10.1.2.1 |
| g_i | degeneracy factor of atomic level i | | 2.1.1 |
| $g(T)$ | used in calculation of burn fraction | (4.74) | 4.4.3.4 |
| H_p | poloidal magnetic field | (3.54) | 3.6.1 |
| H_t | toroidal magnetic field | (3.51) | 3.6 |
| H_0 | scale height | (1.2) | |
| I | moment of inertia | (9.85) | 9.4.2 |
| $I_{e,\text{sat}}$ | electron saturation current of a probe | (7.29) | 7.4.2 |
| $I_{i,\text{sat}}$ | ion saturation current of a probe | (7.27) | 7.4.1 |
| I_p | probe current | | 7.4 |
| I_N | particle flux | (5.14) | 5.1.4 |
| I_P | momentum flux | (5.16) | 5.1.4 |

| | | | |
|--------------------------|---|-----------|----------|
| I_{ph} | Photoelectron current | (10.3) | 10.1.2 |
| j | current density | (4.29) | 4.3.2 |
| j_e | electron current density | (4.29) | 4.3.2 |
| j_i | ion current density | (4.29) | 4.3.2 |
| $j_{\text{max,Pierce}}$ | maximum current in a Pierce diode | (8.39) | |
| j_t | toroidal current density | (3.53) | 3.6.3 |
| $\hat{\mathbf{j}}$ | Fourier amplitude of \mathbf{j} | (6.8) | 6.1.2 |
| J | longitudinal invariant | | 3.4.3 |
| J_0 | initial angular momentum | | 7.5.4 |
| k | wavenumber | (6.8) | 6.1.2 |
| K | normalized wavenumber | (10.90) | 10.4.1.2 |
| k_{I} | spatial growth rate | (8.20) | 8.1.5 |
| k_{B} | Boltzmann's constant | | 2.1 |
| \mathbf{kk} | tensor product of wave vecors | (6.27) | 6.2 |
| k_+, k_- | wavenumbers of beam modes | (8.26) | 8.3.2 |
| ℓ | length scale | | 2.2.2 |
| L_{b} | inductance of bulk plasma | (11.17) | 11.2.1 |
| m_{a} | mass of an atom | (4.49) | 4.4.1 |
| m_{e} | electron mass | | |
| m_{i} | ion mass | | |
| m^* | effective mass describing collisions | (6.43) | 6.3.2 |
| m_{d} | dust mass | (10.32) | 10.2.1.1 |
| m_{e}^* | effective electron mass | | 6.3.2 |
| m_{\odot} | solar mass | Table 1.1 | 1.2 |
| M | Mach number | (7.18) | 7.3.2 |
| \mathbf{M} | magnetic dipole moment | | 3.1.3 |
| M_{s} | total mass of spherical pellet | (4.75) | 4.4.3.4 |
| n | density | | 2.1 |
| n_{co} | cut-off density | (6.50) | 6.4 |
| n_{e} | electron density | | 2.1 |
| n_{e0} | unperturbed electron density | | 2.2.1 |
| n_{i} | ion density | | 2.1 |
| n_{i0} | unperturbed ion density | | 2.2.1 |
| n_{A^+} | ion density | | 2.1.2 |
| n_i | population density of atomic state i | (2.10) | 2.1.1 |
| N | number of particles | | |
| $N(r)$ | number of particles inside r | (10.72) | 10.3.4 |
| N_{a} | number of atomic targets | (4.13) | 4.2.2 |
| N_{De} | number of particles in electron Debye sphere | (2.33) | 2.3.1 |
| $N^{(\alpha)}$ | total number of particles of species α | (9.5) | 9.1.1 |
| \mathcal{N} | refractive index | (6.24) | 6.1.6 |
| \mathcal{N}_{L} | refractive index of L-mode | (6.96) | 6.6.2 |
| \mathcal{N}_{R} | refractive index of R-mode | (6.95) | 6.6.2 |

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|-------------------------|--|---------|----------|
| p | pressure | | 2.1 |
| P | Stix parameter | (6.90) | 6.6 |
| P | Havnes parameter | (10.27) | 10.1.6 |
| $p(t)$ | time-dependent probability | (4.44) | 4.3.4 |
| P_{br} | Power in bremsstrahlung | (4.59) | 4.4.2.1 |
| P_{DT} | Power from D–T reaction | (4.63) | 4.4.2 |
| P_e, P_1 | probability of capturing an electron (ion) | (10.18) | 10.1.5 |
| P_{fus} | Power from fusion reaction | | 4.4.2.5 |
| P_{ij} | stress tensor | (5.29) | 5.1.5 |
| P_{H} | heat loss rate | (4.62) | 4.4.2 |
| p_{mag} | magnetic pressure | (5.47) | 5.2.2 |
| P_x | x -component of momentum vector | (5.23) | 5.1.4 |
| Q | electric charge | | 2.2.1 |
| Q | quality factor of a resonator | | 6.4.4 |
| q_{d} | dust charge | (10.11) | 10.1.3.2 |
| Q_{DT} | fusion yield of D–T reaction | | 4.4.2.2 |
| Q_{α} | energy of α -particles | | 4.4.2.4 |
| r | radius | | 2.2.1 |
| r_{L} | Larmor radius | (3.5) | 3.1.2 |
| R | major radius of a torus | | 3.6.3 |
| R | equivalent resistance of charging characteristic | (10.15) | 10.1.4 |
| R_{b} | resistance of bulk plasma | (11.17) | 11.2.1 |
| r_{C} | Coulomb radius | (10.55) | 10.2.4 |
| $R(T)$ | recombination rate | | 2.1.2 |
| R_{c} | radius of curvature | | 5.2.2 |
| R_{C} | radius of a Coulomb ball | (10.81) | 10.3.4 |
| R_{hs} | radius of hot spot | (4.70) | 4.4.3.3 |
| R_{m} | mirror ratio | | 3.4.2 |
| R_1, R_2 | electrical resistors | | 2.2.1 |
| R_{total} | resistance of parallel circuit | | 2.2.1 |
| s | distance | | 2.2.1 |
| S | entropy | (2.3) | 2.1.1.1 |
| S | Stix parameter | (6.90) | 6.6 |
| s_1, s_2 | sheath thickness | (11.18) | 11.2.2 |
| $S(\mathbf{k}, \omega)$ | spectral energy density | (10.96) | 10.4.2 |
| $S(W_{\lambda})$ | energy density of solar spectrum | (10.3) | 10.1.2 |
| S_{ion} | ionization rate | (4.18) | 4.2.3 |
| $S(T)$ | ionization rate | | 2.1.2 |
| T | temperature | | |
| \mathcal{T} | tension | | |
| T_{d} | dust temperature | | 10.4.3 |
| T_{e} | electron temperature | | 2.1 |
| T_{i} | ion temperature | | 2.1 |
| Δt_k | variable time step for charge capture | (10.20) | 10.1.5 |

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|----------------------------------|---|---------|----------|
| T_{ph} | effective temperature of photoelectrons | (10.4) | 10.1.2 |
| \mathbf{u} | drift velocity | | 5.1.1 |
| U_1, U_2 | sheath voltage | (11.22) | 11.2.2 |
| u_i | ion streaming velocity | | 7.2 |
| U_b | voltage drop in bulk plasma | (11.16) | 11.2.1 |
| U_{bd} | breakdown voltage | (11.6) | 11.1.3.1 |
| U_{dc} | self bias voltage | (11.27) | 11.2.4 |
| U_{ind} | induction voltage | | 5.1.1 |
| U_n | normal cathode fall voltage | | 11.1.3 |
| U_p | probe voltage | | 7.4 |
| U_{rf} | radio-frequency voltage | (11.27) | 11.2.4 |
| v | velocity | | |
| \mathbf{v} | velocity vector | | 3.1 |
| v_x, v_y, v_z | components of the velocity vector | | 3.1 |
| \bar{v}_x, \bar{v}_y | average velocities | (4.46) | 4.3.4 |
| v_A | Alfvén velocity | (5.83) | 5.3.5 |
| v_b | velocity of a beam electron | (8.11) | 8.1.4 |
| v_c | cut-off velocity | (9.24) | 9.2.1 |
| v_B | Bohm velocity | (7.17) | 7.3.2 |
| v_d | drift velocity | (4.27) | 4.3.1 |
| v_D | diamagnetic drift velocity | (5.50) | 5.2.3 |
| v_E | $E \times B$ drift velocity | (3.12) | 3.1.4 |
| v_{exhaust} | exhaust velocity | | 4.4.3.2 |
| v_g | gravitational drift velocity | (3.14) | 3.1.5 |
| \mathbf{v}_{gr} | group velocity vector | (6.23) | 6.1.5 |
| v_m | mass flow velocity | (5.56) | 5.3.1 |
| v_p | polarisation drift velocity | (3.47) | 3.5.1 |
| v_R | curvature drift velocity | (3.23) | 3.2.3 |
| v_{shell} | velocity of imploding shell | (4.69) | 4.4.3.2 |
| v_{th} | mean thermal speed | (4.7) | 4.1.3 |
| v_T | most probable speed | (4.4) | 2.3.1 |
| v_0 | initial beam velocity | (8.3) | 8.1.2 |
| v_+, v_-, \bar{v} | contributions to the Pierce mode | (8.33) | 8.3.3 |
| v_{\perp} | perpendicular velocity | | 3.4.2 |
| $v_{\nabla B}$ | gradient drift velocity | (3.21) | 3.2.2 |
| \mathbf{v}_{φ} | phase velocity | (6.18) | 6.1.4 |
| W | energy | | 2.1.1 |
| $W(x)$ | charge assignment function | (9.79) | 9.4.1 |
| W_b | binding energy | | |
| W_{ex} | excess energy | | |
| W_0 | initial energy | | 7.5.4 |
| W_{ion} | ionisation energy | | 4.2.4 |
| W_{kin} | kinetic energy | (4.8) | 4.1.3 |
| W_m | maximum energy in secondary emission | (10.2) | 10.1.1 |
| $\langle W_{\text{kin}} \rangle$ | mean beam kinetic energy | (8.17) | 8.1.4 |

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|--|--|----------------|----------|
| W_{pot} | potential energy | (9.84) | 9.4.2 |
| W_{R} | work function in Richardson's law | (11.10) | 11.1.5 |
| W_{tot} | total energy | (8.40), (9.86) | 9.4.2 |
| W_{Y} | energy of Yukawa interaction | (10.63) | 10.2.5 |
| W_{\perp} | energy of perpendicular motion | (3.49) | 3.5.2 |
| x_{min} | position of potential minimum in diode | (9.25) | 9.2.1 |
| Z | partition function | | 2.1.1 |
| Z_{b} | impedance of bulk plasma | (11.16) | 11.2.1 |
| Z_{d} | dust charge number = $ q_{\text{d}} /e$ | (10.13) | 10.1.3.2 |
| Z_j | charge number of species j | | 2.2.2 |
| α | index denoting particle species | (6.80) | 6.6 |
| α | Townsend's electron multiplication factor | (11.1) | 11.1.3.1 |
| α_{b} | beam fraction in beam-plasma system | (8.3) | 8.1.2 |
| α_{p} | Pierce parameter | (8.37) | 8.3.1 |
| $\alpha(L)$ | angle of Faraday rotation | (6.100) | 6.6.2.1 |
| β | ratio of kinetic and total pressure | (5.51) | 5.2.3 |
| γ | growth rate | | 8.1.3 |
| γ | coefficient for secondary emission by ion impact | (11.4) | 11.1.3.1 |
| Γ | coupling parameter | (2.15) | 2.1.3 |
| Γ_{a} | ambipolar flux | (4.34) | 4.3.3.1 |
| $\Gamma_{\text{e,i}}$ | flux of electrons (ions) | (4.31) | 4.3.3 |
| δ | accomodation coefficient for Epstein friction | (10.42) | 10.2.2 |
| δ_0 | skin depth | (11.41) | 11.3.1 |
| δ_{cl} | collisionless skin depth | (11.43) | 11.3.1 |
| $\delta(W)$ | secondary emission coefficient | (10.1) | 10.1.1 |
| δ_{m} | maximum of $\delta(W)$ | (10.2) | 10.1.1 |
| ε | dielectric function for cold plasma | (6.45) | 6.4 |
| ε | ... for beam-plasma system | (8.2) | 8.1.2 |
| ε | ... for ion-acoustic wave | (6.75) | 6.5.3 |
| $\boldsymbol{\varepsilon}$ | dielectric tensor | (6.89) | 6.6 |
| $\varepsilon_{xx}, \varepsilon_{yy}, \varepsilon_{zz}$ | elements of the dielectric tensor | (6.34) | 6.3.1 |
| η | resistivity | (4.22) | 4.2.5 |
| η | efficiency of energy conversion | (4.63) | 4.4.2 |
| η_{c} | normalized cloud potential | (10.25) | 10.1.6 |
| η_{f} | normalized grain potential | (10.25) | 10.1.6 |
| η_{s} | Spitzer resistivity | (4.23) | 4.2.5 |
| θ | angle w.r.t. magnetic field direction | | 3.4.2 |
| θ | normalized frequency for Pierce modes | | 8.3.3 |
| θ_{c} | resonance cone angle | (6.105) | 6.7 |
| θ_{m} | loss cone angle | (3.56) | 3.6.3 |
| λ | wavelength | | 6.4 |
| λ | Lagrange multiplier | | 2.1.1.1 |
| $\ln(\Lambda)$ | Coulomb logarithm | (10.61) | 10.2.4 |

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|---|---------------------------------------|---------|---------------|
| λ_B | de Broglie wavelength | (2.36) | 2.3.2 |
| λ_D | Debye length | | 2.2.1 |
| λ_{De} | Electron Debye length | (2.28) | 2.2.1 |
| λ_{Di} | Ion Debye length | (2.28) | 2.2.1 |
| λ_{\max} | maximum of Planck curve | (2.14) | 2.1.2 |
| λ_{\min} | shortest wavelength in crystal | | 10.4.1.1 |
| λ_{mfp} | mean free path | (4.14) | 4.2.2 |
| λ_s | modified shielding length | (10.56) | 10.2.4 |
| μ | Lagrange multiplier | | 2.1.1.1 |
| μ | magnetic moment | (3.34) | 3.3.2 |
| μ | ion-to-electron mass ratio | | |
| μ | Mach cone angle | (10.94) | 10.4.1.7 |
| μ_e | electron mobility | (4.28) | 4.3.1 |
| μ_i | ion mobility | (4.28) | 4.3.1 |
| ν_{coll} | collision frequency | (4.15) | 4.2.2 |
| ν_{DT} | deuterium-tritium collision frequency | (4.60) | 4.4.2.2 |
| ν_{ei} | electron-ion collision frequency | (4.21) | 4.2.5 |
| ν_{ion} | ionization frequency | (4.17) | 4.2.3 |
| ν_m | momentum loss frequency | (4.25) | 4.3.1 |
| $\xi(W_\lambda)$ | photoelectric efficiency | (10.3) | 10.1.2 |
| \mathcal{E}_d | normalized dust collision frequency | (10.90) | 10.4.1.2 |
| ρ | charge density | (5.1) | 5.1.1 / 5.1.3 |
| ρ_m | mass density in MHD | (5.38) | 5.2 |
| ρ_d | mass density of dust material | | 10.2.1 |
| ρ_p | assigned charge to gridpoint p | (9.78) | 9.4.1 |
| ρ_0 | initial mass density | | 4.4.3.4 |
| ρR | density-radius product for a pellet | | 4.4.3.4 |
| σ | cross section | (4.13) | 4.2.2 |
| σ | conductivity | | 4.3.2 |
| σ_c | cross section for charge collection | (10.5) | 10.1.3 |
| $\sigma_{e,i}$ | electron (ion) conductivity | (4.30) | 4.3.2 |
| $\sigma_{xx}, \sigma_{yy}, \sigma_{zz}$ | elements of conductivity tensor | (6.32) | 6.3.1 |
| $\boldsymbol{\sigma}$ | conductivity tensor | (4.47) | 4.3.4 |
| σ_{ion} | cross-section for ionization | (4.16) | 4.2.3 |
| τ | elapsed time | (9.20) | 9.2.1 |
| τ | relaxation time of dust charge | (10.16) | 10.1.4 |
| τ | temperature ratio T_e/T_i | (10.26) | 10.1.6 |
| τ_B | magnetic diffusion time | (5.62) | 5.3.2 |
| τ_c | inertial confinement time | (4.68) | 4.4.3.1 |
| τ_E | energy confinement time | | 4.4.2.5 |
| φ | phase angle of a wave | (6.16) | 6.1.4 |
| $\varphi_{\text{air}}, \varphi_p$ | phase angle in air (plasma) | | 6.4.3 |
| φ_1, φ_2 | phase angles of second harmonic | | 6.4.3 |
| Φ | electric potential | | 2.2.1 / 7.2 |
| Φ_f | floating potential (probe) | (7.34) | 7.4.4 |

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|---------------|--|---------|-------------|
| Φ_f | floating potential (dust grain) | (10.8) | 10.1.3.1 |
| Φ_p | potential at gridpoint p | (9.80) | 9.4.1 |
| Φ_p | plasma potential | | 7.4 |
| Φ_m | magnetic flux | | 5.1.1 |
| Φ_{\min} | minimum potential in a diode | (9.28) | 9.2.2 |
| χ | empirical constant for photoemission | (10.4) | 10.1.2 |
| χ | scattering angle | (10.57) | 10.2.4 |
| χ_b | permittivity of beam electrons | (8.3) | 8.1.2 |
| χ_d | permittivity of dust system | (10.99) | 10.4.3 |
| χ_e | permittivity of cold electrons | (8.21) | 8.2 |
| χ_i | permittivity of ions | (8.21) | 8.2 |
| χ_p | permittivity of plasma electrons | (8.2) | 8.1.2 |
| ψ | angle between \mathbf{k} and \mathbf{B} | (6.91) | 6.6.1 |
| ω | angular frequency | | 3.1 / 6.6.2 |
| Ω | normalized frequency | | 10.4.1.2 |
| ω_{br} | breathing frequency of dust cluster | (10.69) | 10.2.5 |
| ω_c | cyclotron frequency | (3.4) | 3.1.2 |
| ω_{ce} | electron cyclotron frequency | | 3.1.2 |
| ω_{ci} | ion cyclotron frequency | (6.84) | 6.6.1 |
| ω_I | imaginary part = growth rate | (8.9) | 8.1.2 |
| Ω_L | normalized frequency of long. mode | (10.90) | 10.4.1.2 |
| ω_{lh} | lower hybrid frequency | (6.104) | 6.6.3 |
| ω_{pd} | dust plasma frequency | (10.98) | 10.4.3 |
| ω_{pe} | electron plasma frequency | (2.32) | 2.2.3 |
| ω_{pi} | ion plasma frequency | (6.75) | 6.5.3 |
| ω_R | real part of wave frequency | (8.8) | 8.1.2 |
| Ω_T | norm. frequency of transverse mode | (10.91) | 10.4.1.2 |
| ω_{uh} | upper hybrid frequency | (6.103) | 6.6.3 |
| ω_0 | plasma frequency for strongly coupled system | (10.89) | 10.4.1.1 |

Appendix: Constants and Formulas

“Reeling and Writhing, of course, to begin with,” the Mock Turtle replied; “and then the different branches of Arithmetic—Ambition, Distraction, Uglification and Derision.”

Lewis Carroll, Alice in Wonderland

1 Physical Constants

The physical constants are given here in SI-units with four digits accuracy. For problem solving in plasma physics, often two digits are sufficient in view of the uncertainty of measured plasma parameters.

Table 1 Physical constants

| | | | | |
|----------------------------------|------------------|---|-------------------------|-------------------------------------|
| Electron mass | m_e | = | 9.109×10^{-31} | kg |
| Proton mass | m_p | = | 1.673×10^{-27} | kg |
| Proton-electron mass ratio | m_p/m_e | = | 1836 | |
| Elementary charge | e | = | 1.602×10^{-19} | A s |
| Specific charge of electron | e/m_e | = | 1.759×10^{11} | C kg ⁻¹ |
| Speed of light in vacuum | c | = | 2.998×10^8 | m s ⁻¹ |
| Permittivity of free space | ϵ_0 | = | 8.854×10^{-12} | A s V ⁻¹ m ⁻¹ |
| | μ_0 | = | 1.257×10^{-6} | V s A ⁻¹ m ⁻¹ |
| Boltzmann constant | k_B | = | 1.381×10^{-23} | J K ⁻¹ |
| Temperature associated with 1 eV | e/k_B | = | 11,600 | K V ⁻¹ |
| Stefan-Boltzmann constant | σ | = | 5.670×10^{-8} | W m ⁻² K ⁻⁴ |
| Planck’s constant | h | = | 6.626×10^{-34} | Js |
| | $\hbar = h/2\pi$ | = | 1.055×10^{-34} | Js |
| Avogadro’s constant | N_A | = | 6.022×10^{23} | mol ⁻¹ |
| Molar gas constant | R | = | 8.314 | J K ⁻¹ mol ⁻¹ |
| Standard temperature | | = | 273.15 | K |
| Earth mass | M_E | = | 5.974×10^{24} | kg |
| Mean Earth radius | R_E | = | 6.371×10^6 | m |
| Universal gravitational constant | G | = | 6.673×10^{-11} | N m ² kg ⁻² |
| Gravitational acceleration | $g = GM_E/R_E^2$ | = | 9.807 | ms ⁻² |

2 List of Useful Formulas

This compilation was inspired by the NRL plasma formulary, which is available free of charge at <http://wwwppd.nrl.navy.mil/nrlformulary/>. However, SI-units are used here for consistency with the rest of the book. Temperatures are given in eV, as indicated.

2.1 Lengths

The mass number of an ion is $\mu = m_i/m_p$.

- electron Debye length

$$\lambda_{\text{De,Di}} = 7.43 \times 10^3 \text{ m} \sqrt{\frac{T_{e,i}(\text{eV})}{n_{e,i}(\text{m}^{-3})}}$$

- thermal electron gyroradius

$$r_{\text{Le}} = \frac{v_{\text{Te}}}{\omega_{\text{ce}}} = 3.37 \times 10^{-6} \text{ m} \frac{\sqrt{T_e(\text{eV})}}{B(\text{T})}$$

- thermal ion gyroradius

$$r_{\text{Li}} = \frac{v_{\text{Ti}}}{\omega_{\text{ci}}} = 1.45 \times 10^{-4} \text{ m} \frac{\sqrt{\mu T_i(\text{eV})}}{B(\text{T})}$$

2.2 Frequencies

- electron plasma frequency

$$\omega_{\text{pe}} = \sqrt{\frac{n_e e^2}{\epsilon_0 m_e}} = 56.4 \text{ s}^{-1} \sqrt{n_e(\text{m}^{-3})}$$

- ion plasma frequency

$$\omega_{\text{pi}} = \sqrt{\frac{n_i Z^2 e^2}{\epsilon_0 m_i}} = 1.32 \text{ s}^{-1} Z \sqrt{\frac{n_i(\text{m}^{-3})}{\mu}}$$

- electron gyrofrequency

$$\omega_{\text{ce}} = \frac{eB}{m_e} = 1.76 \times 10^{11} \text{ s}^{-1} B(\text{T})$$

- ion gyrofrequency

$$\omega_{ci} = \frac{ZeB}{m_i} = 9.58 \times 10^7 \text{ s}^{-1} \frac{Z}{\mu} B \text{ (T)}$$

2.3 Velocities

- electron thermal speed

$$v_{Te} = \sqrt{\frac{2k_B T_e}{m_e}} = 5.93 \times 10^5 \text{ m s}^{-1} \sqrt{T_e \text{ (eV)}}$$

- ion thermal speed

$$v_{Ti} = \sqrt{\frac{2k_B T_i}{m_i}} = 1.38 \times 10^4 \text{ m s}^{-1} \sqrt{\frac{T_i \text{ (eV)}}{\mu}}$$

- ion sound speed

$$C_s = \sqrt{\frac{k_B(T_e + 3T_i)}{m_i}} = 9.79 \times 10^3 \text{ m s}^{-1} \sqrt{\frac{(T_e + 3T_i) \text{ (eV)}}{\mu}}$$

- Alfvén speed

$$v_A = \frac{B}{\sqrt{\mu_0 n_i m_i}} = 2.18 \times 10^{16} \text{ m s}^{-1} \frac{B \text{ (T)}}{\sqrt{\mu n_i \text{ (m}^{-3}\text{)}}}$$

3 Useful Mathematics

3.1 Vector Relations

The definitions of dot product and vector product of two vectors can be summarized as follows:

$$\begin{aligned}\mathbf{A} \cdot \mathbf{B} &= A_x B_x + A_y B_y + A_z B_z \\ \mathbf{A} \times \mathbf{B} &= \begin{vmatrix} \mathbf{e}_x & \mathbf{e}_y & \mathbf{e}_z \\ A_x & A_y & A_z \\ B_x & B_y & B_z \end{vmatrix} \\ &= \mathbf{e}_x(A_y B_z - A_z B_y) + \mathbf{e}_y(A_z B_x - A_x B_z) + \mathbf{e}_z(A_x B_y - A_y B_x) \\ \mathbf{A} \cdot \mathbf{B} &= \mathbf{B} \cdot \mathbf{A} \\ \mathbf{A} \times \mathbf{B} &= -\mathbf{B} \times \mathbf{A}\end{aligned}$$

The operator $\mathbf{A} \cdot \nabla$ is a scalar operator

$$\mathbf{A} \cdot \nabla = A_x \frac{\partial}{\partial x} + A_y \frac{\partial}{\partial y} + A_z \frac{\partial}{\partial z}.$$

The gradient of a vector function is defined as a tensor, which can be written as a matrix (see next paragraph)

$$\nabla \mathbf{A} = \begin{pmatrix} \frac{\partial A_x}{\partial x} & \frac{\partial A_x}{\partial y} & \frac{\partial A_x}{\partial z} \\ \frac{\partial A_y}{\partial x} & \frac{\partial A_y}{\partial y} & \frac{\partial A_y}{\partial z} \\ \frac{\partial A_z}{\partial x} & \frac{\partial A_z}{\partial y} & \frac{\partial A_z}{\partial z} \end{pmatrix}$$

The following list gives some standard rules for operations involving multiple dot products, vector products, and derivatives. Note that differential operators act only on the term on their r.h.s., A_c means that A is not affected by the differential operator. f is a scalar function.

$$\begin{aligned}\mathbf{A} \cdot (\mathbf{B} \times \mathbf{C}) &= \mathbf{B} \cdot (\mathbf{C} \times \mathbf{A}) = \mathbf{C} \cdot (\mathbf{A} \times \mathbf{B}) \\ \mathbf{A} \times (\mathbf{B} \times \mathbf{C}) &= (\mathbf{A} \cdot \mathbf{C})\mathbf{B} - (\mathbf{A} \cdot \mathbf{B})\mathbf{C} \\ \nabla(fg) &= f\nabla g + g\nabla f \\ \nabla \cdot (f\mathbf{A}) &= f\nabla \cdot \mathbf{A} + \mathbf{A} \cdot \nabla f \\ \nabla \times (f\mathbf{A}) &= f\nabla \times \mathbf{A} + \nabla f \times \mathbf{A}_c \\ \nabla \cdot (\mathbf{A} \times \mathbf{B}) &= \mathbf{B} \cdot (\nabla \times \mathbf{A}) - \mathbf{A} \cdot (\nabla \times \mathbf{B}) \\ \nabla \times (\mathbf{A} \times \mathbf{B}) &= \mathbf{A}(\nabla \cdot \mathbf{B}) - \mathbf{B}(\nabla \cdot \mathbf{A}) + (\mathbf{B} \cdot \nabla)\mathbf{A} - (\mathbf{A} \cdot \nabla)\mathbf{B} \\ \nabla(\mathbf{A} \cdot \mathbf{B}) &= (\mathbf{A} \cdot \nabla)\mathbf{B} + (\mathbf{B} \cdot \nabla)\mathbf{A} + \mathbf{A} \times (\nabla \times \mathbf{B}) + \mathbf{B} \times (\nabla \times \mathbf{A}) \\ \mathbf{A} \times (\nabla \times \mathbf{B}) &= (\nabla \mathbf{B}) \cdot \mathbf{A}_c - (\mathbf{A} \cdot \nabla)\mathbf{B} \\ \Delta \mathbf{A} &= \nabla(\nabla \cdot \mathbf{A}) - \nabla \times (\nabla \times \mathbf{A}) \\ \nabla \cdot (\nabla \times \mathbf{A}) &= 0 \\ \nabla \times (\nabla f) &= 0\end{aligned}$$

3.2 Matrices and Tensors

Matrices describe the mapping of a vector into a new vector, usually of different length and direction. A matrix is a special tensor of rank two. There are also tensors of higher rank, which we, however, omit from the discussion.

The product of a 3×3 matrix \mathbf{M} and a vector \mathbf{A} can be written as

$$\mathbf{M} \cdot \mathbf{A} = \begin{pmatrix} M_{xx} & M_{xy} & M_{xz} \\ M_{yx} & M_{yy} & M_{yz} \\ M_{zx} & M_{zy} & M_{zz} \end{pmatrix} \cdot \begin{pmatrix} A_x \\ A_y \\ A_z \end{pmatrix} = \begin{pmatrix} M_{xx}A_x + M_{xy}A_y + M_{xz}A_z \\ M_{yx}A_x + M_{yy}A_y + M_{yz}A_z \\ M_{zx}A_x + M_{zy}A_y + M_{zz}A_z \end{pmatrix}.$$

The elements of the resulting vector are the dot product (scalar product) of a row of the matrix \mathbf{M} with the vector \mathbf{A} .

Matrices can also be used to represent systems of linear equations. The following homogeneous system of equations

$$\begin{aligned} 3x + 5y - 2z &= 0 \\ 2x - 3y + z &= 0 \\ 5x + 2y - z &= 0 \end{aligned}$$

can be rewritten in matrix form as

$$\begin{pmatrix} 3 & 5 & -2 \\ 2 & -3 & 1 \\ 5 & 2 & -1 \end{pmatrix} \cdot \begin{pmatrix} x \\ y \\ z \end{pmatrix} = 0.$$

This system of equations has a non-zero solution, when the determinant of the matrix vanishes

$$\begin{vmatrix} 3 & 5 & -2 \\ 2 & -3 & 1 \\ 5 & 2 & -1 \end{vmatrix} = 3(3 - 2) + 5(5 + 2) - 2(4 + 15) = 0$$

The unit tensor is

$$I_{\alpha\beta} = \delta_{\alpha\beta} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}.$$

The dyadic product of two vectors \mathbf{A} and \mathbf{B} is a tensor of rank two containing the products of the vector components, $\mathbf{T}_{\alpha\beta} = A_\alpha B_\beta$,

$$\mathbf{A} \mathbf{B} = \mathbf{T} = \begin{pmatrix} A_x B_x & A_x B_y & A_x B_z \\ A_y B_x & A_y B_y & A_y B_z \\ A_z B_x & A_z B_y & A_z B_z \end{pmatrix}.$$

3.3 *The Theorems of Gauss and Stokes*

Assume that V is a volume bounded by a closed surface S , with dS positive outward from the enclosed volume, then

$$\oint_S \mathbf{A} \cdot dS = \int_V (\nabla \cdot \mathbf{A}) dV .$$

If S is an open surface bounded by the contour C , of which the line element is ds , then

$$\oint_C \mathbf{A} \cdot ds = \int_S (\nabla \times \mathbf{A}) \cdot dS .$$

Solutions

“Forty-two!”

Douglas Adams, The Hitchhikers Guide to the Galaxy

Problems of Chapter 2

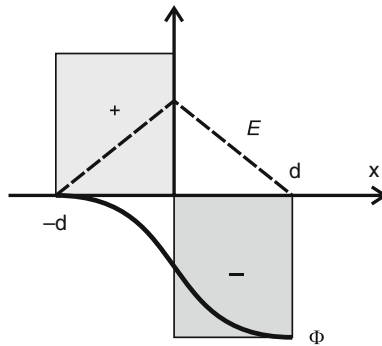
2.1

$$\lambda_{De} = \sqrt{\frac{\epsilon_0 k_B T_e}{n_e e^2}} = \sqrt{\frac{\epsilon_0 k_B}{e^2}} \sqrt{\frac{T_e}{n_e}} = 69.0 \text{ m} \sqrt{\frac{T_e(\text{K})}{n_e(\text{m}^{-3})}}$$

2.2 (a) $\lambda_{De} = \lambda_{Di} = 69\sqrt{3000 \times 10^{-12}} \text{ m} = 3.8 \times 10^{-3} \text{ m}$.

(b) Note that $3 \text{ eV} \hat{=} 3 \times 11600 \text{ K}$. $\lambda_{De} = 1.3 \times 10^{-4} \text{ m}$, $\lambda_{Di} = 1.2 \times 10^{-5} \text{ m}$.

2.3 Poisson’s equation states that the curvature of the potential is proportional to the (negative) space charge. $\Phi'' = -en_i/\epsilon_0$. (a) The electric field increases linearly in the positive space charge region from $E(-d) = 0$ to $E(0) = E_{\text{max}}$ and decreases in the negative space charge region to $E(d) = 0$. Hence, there is no electric field at the edges of the quasineutral plasma. The potential decreases in the positive space charge region as $\Phi(x) = -\frac{1}{2}n_i e(x + d)^2/\epsilon_0$ and reaches $\Phi(0) = -9.0 \times 10^3 \text{ V}$. In the negative space charge region, $\Phi(x)$ has the opposite curvature and reaches a final value $\Phi(d) = -18.0 \times 10^3 \text{ V}$.



2.4 Calculate the derivatives

$$\Phi(r) = \frac{a}{r} f(r), \quad \Phi' = -\frac{a}{r^2} f(r) + \frac{a}{r} f', \quad \Phi'' = \frac{2a}{r^3} f - \frac{2a}{r^2} f' + \frac{a}{r} f''$$

Inserting into (2.21) gives

$$\frac{a}{r} \left[f'' - \frac{1}{\lambda_D^2} f \right] = 0.$$

2.5 Inserting the Wigner-Seitz radius $a_{\text{WS}} = [3/(4\pi n_i)]^{1/3}$ into (2.15) gives

$$\Gamma_i = \frac{(4\pi/3)^{1/3}}{4\pi} \frac{e^2 n_i^{1/3}}{\varepsilon_0 k_B T_i} = \frac{1}{3} \left(\frac{4\pi}{3} n_i \lambda_{\text{Di}}^3 \right)^{-2/3} = \frac{1}{3} N_{\text{Di}}^{-2/3}$$

2.6 Starting from the definitions $S = -k_B \sum_i n_i \ln n_i$ and $U = \sum_i n_i W_i$ we use the thermodynamic definition of temperature $1/T = \partial S / \partial U$.

$$\begin{aligned} \frac{1}{T} &= \frac{\partial S}{\partial \lambda} \frac{\partial \lambda}{\partial U} = \frac{-k_B \sum_i \left[\frac{\partial n_i}{\partial \lambda} (\lambda W_i - \ln Z) + \frac{\partial n_i}{\partial \lambda} \right]}{\sum_i \frac{\partial n_i}{\partial \lambda} W_i} \\ &= \frac{-k_B \lambda \sum_i \frac{\partial n_i}{\partial \lambda} W_i + k_B (\ln Z - 1) \sum_i \frac{\partial n_i}{\partial \lambda}}{\sum_i \frac{\partial n_i}{\partial \lambda} W_i} = k_B \lambda. \end{aligned}$$

Using $\sum_i n_i = 1$, we obtain the result $\lambda = (k_B T)^{-1}$.

Problems of Chapter 3

3.1 Ampere's law states that the integral of the magnetic field strength H along a closed path equals the current flowing through the area bounded by this path, $\oint \mathbf{H} \cdot d\mathbf{s} = I$. Choose a circle of radius r centered at the axis of the wire for the path. Then, for any $r < a$ the current flow through this circle is the fraction $I r^2/a^2$ and we obtain

$$2\pi r H_\varphi = I \frac{r^2}{a^2} \quad \Rightarrow \quad H_\varphi = \frac{I r}{2\pi a^2},$$

which increases linearly to a maximum $H_\varphi = I/(2\pi a)$ at $r = a$. For $r > a$ the encircled current is always I and $H_\varphi = I/(2\pi r)$ becomes a decreasing function of radius.

3.2 The current $I(r)$ flowing through a circle of radius $r < a$ determines the magnetic field

$$I(r) = 2\pi \int_0^r r' j(r') dr' = 2\pi j_0 \left(\frac{r^2}{2} - \frac{r^4}{4a^2} \right) \Rightarrow H_\varphi = j_0 \left(\frac{r}{2} - \frac{r^3}{4a^2} \right).$$

3.3 $B = 49.4 \mu\text{T}$. (a) $\omega_{ce} = 8.7 \times 10^6 \text{s}^{-1}$. (b) $r_{ce} = 0.22 \text{m}$.

3.4 (a) Use $\mathbf{M} \cdot \mathbf{r} = Mr \cos \theta$ to define the angle θ . The unit vector $\mathbf{e}_r = \mathbf{r}/r$.

$$B_r = \mathbf{B} \cdot \mathbf{e}_r = \frac{\mu_0}{4\pi} \frac{3r^2(\mathbf{r} \cdot \mathbf{M}) - r^2(\mathbf{r} \cdot \mathbf{M})}{r^6} = \frac{\mu_0 M}{4\pi} \frac{2 \cos \theta}{r^3}$$

$$B_\theta = |\mathbf{e}_r \times \mathbf{B}| = \frac{\mu_0 M}{4\pi} \frac{\sin \theta}{r^3}.$$

(b) Solve the last line for M , insert $\theta = 90^\circ$, $B_\theta = 30 \mu\text{T}$ and use the Earth radius plus about (100–200) km altitude for the ionosphere to obtain $M \approx 8 \times 10^{22} \text{A m}^{-2}$.

3.5 At the magnetic equator, $\theta = 90^\circ$ and the magnetic field has only a θ -component $B_\theta = (\mu_0 M/4\pi)r^{-3}$. (a) Hence, $dB_\theta/dr = -3(\mu_0 M/4\pi)r^{-4}$ and $R_c = r/3 = (R_E + 500 \text{km})/3 = 2,290 \text{km}$. (b) $v_R = 2v_{\nabla B} = 6W/(qrB)$. At $H = 500 \text{km}$ altitude, the equatorial magnetic field of $30 \mu\text{T}$ has decreased by a factor $[R_E/(R_E + H)]^3 = 0.80$ to $24 \mu\text{T}$. Then $v_R = 0.11 \text{m s}^{-1}$.

3.6 Starting from the equations of motion

$$\dot{v}_x = -\frac{e}{m_e} E - \omega_{ce} v_y \quad \text{and} \quad \dot{v}_y = \omega_{ce} v_x$$

we see that the electron velocity performs harmonic oscillations at the frequency ω_{ce} and $v_x = v_\perp \sin(\omega_{ce} t)$. There is no cosine term because $v_x(0) = 0$. Then, $v_y = \omega_{ce} \int v_x dt + C = v_\perp [1 - \cos(\omega_{ce} t)]$ to fulfill $v_y(0) = 0$. From $\dot{v}_x(0) = 0$ we obtain $v_\perp = -E/B$. Hence,

$$v_x = -\frac{E}{B} \sin(\omega_{ce} t), \quad v_y = \frac{E}{B} [1 - \cos(\omega_{ce} t)]$$

$$x = \frac{E}{B\omega_{ce}} [\cos(\omega_{ce} t) - 1], \quad y = -\frac{E}{B} t + \frac{E}{B\omega_{ce}} \sin(\omega_{ce} t)$$

3.7 The differential equation for a field line with the dipole source at the origin reads

$$\frac{dz}{dx} = \frac{2z}{3x} - \frac{1}{3} \frac{x}{z}.$$

Set $z = wx$ to obtain $dz/dx = w + x(dw/dx)$. Inserting into the differential equation

$$x \frac{dw}{dx} = -\frac{1}{3}w - \frac{1}{3} \frac{1}{w} \Rightarrow \frac{w dw}{w^2 + 1} = -\frac{1}{3} \frac{dx}{x} \Rightarrow \frac{1}{2} \ln(w^2 + 1) = -\frac{1}{3} \ln(x) + C.$$

This results in $w = (-1 + c_1 x^{-2/3})^{1/2}$ and $z = x(-1 + c_1 x^{-2/3})^{1/2}$. The maximum distance x_{\max} of the field line is determined by $z = 0$, which defines $c_1 = x_{\max}^{2/3}$, hence the shape of the field line becomes

$$z = \sqrt{x_{\max}^{2/3} x^{4/3} - x^2}.$$

Problems of Chapter 4

4.1 Let A be the normalizing factor of the velocity distribution $f_M(|v|)$. Then

$$0 = A \frac{d}{dv} v^2 \exp\left(-\frac{mv^2}{2k_B T}\right) = A \left(2v - v^2 \frac{mv}{k_B T}\right) \exp\left(-\frac{mv^2}{2k_B T}\right),$$

which requires that the expression in parantheses vanishes. This gives the desired result $v_T = (2k_B T/m)^{1/2}$.

4.2 The mean thermal velocity is the first moment of the distribution of speeds

$$v_{\text{th}} = 4\pi \left(\frac{m}{2\pi k_B T}\right)^{3/2} \int_0^\infty v^3 \exp\left(-\frac{mv^2}{2k_B T}\right) dv = \left(\frac{8k_B T}{\pi m}\right)^{1/2} \underbrace{\int_0^\infty ye^{-y} dy}_{=1}$$

4.3 Reduce the degree of the velocity moment by partial integration

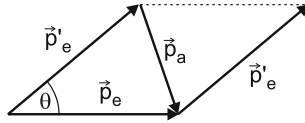
$$\begin{aligned} \int_0^\infty v^4 e^{-av^2} dv &= -\frac{1}{2a} \int_0^\infty v^3 (-2ave^{-av^2}) dv \\ &= -\frac{1}{2a} \underbrace{\left[v^3 e^{-av^2} \right]_0^\infty}_{=0} + \frac{3}{2a} \int_0^\infty v^2 e^{-av^2} dv \\ &= -\frac{3}{4a^2} \underbrace{\left[ve^{-av^2} \right]_0^\infty}_{=0} + \frac{3}{4a^2} \int_0^\infty e^{-av^2} dv = \frac{3}{8a^2} \sqrt{\frac{\pi}{a}}. \end{aligned}$$

Set $a = m/2k_B T$, then the mean square velocity becomes

$$\langle v^2 \rangle = 4\pi \left(\frac{m}{2\pi k_B T} \right)^{3/2} \frac{3\sqrt{\pi}}{8} \left(\frac{2k_B T}{m} \right)^{5/2} = 3 \frac{k_B T}{m}.$$

Finally: $\frac{m}{2} \langle v^2 \rangle = \frac{3}{2} k_B T$.

4.4 Let the electron momentum before and after the collision be \mathbf{p}_e and \mathbf{p}'_e . The scattering angle is θ and the momentum transferred to the atom $\mathbf{p}_a = \mathbf{p}_e - \mathbf{p}'_e$.



Then the kinetic energy transferred to the atom, which equals the energy loss of the electron, is (for $|\mathbf{p}'_e| \approx |\mathbf{p}_e|$)

$$\Delta W = \frac{\mathbf{p}_e^2 - 2\mathbf{p}_e \cdot \mathbf{p}'_e + \mathbf{p}'_e{}^2}{2m_a} \approx \frac{\mathbf{p}_e^2}{2m_e} 2 \frac{m_e}{m_a} [1 - \cos(\theta)].$$

4.5 The average fractional energy loss is

$$\left\langle \frac{\Delta W}{W} \right\rangle = 2 \frac{m_e}{m_a} \frac{1}{4\pi} \int_0^{2\pi} d\varphi \int_0^\pi d\theta \sin\theta [1 - \cos\theta] = 2 \frac{m_e}{m_a} \frac{1}{2} \int_{-1}^1 (1-x) dx = 2 \frac{m_e}{m_a}.$$

4.6 The average velocity \bar{v}_x is given by

$$\begin{aligned} \bar{v}_x &= \frac{E_x v_{m,i}^2}{B_z \omega_{ci}} \int_0^\infty [1 - \cos(\omega_{ci} t)] e^{-v_{m,i} t} dt = \frac{E_x v_{m,i}}{B_z \omega_{ci}} \left[1 - v_{m,i} \int_0^\infty \cos(\omega_{ci} t) e^{-v_{m,i} t} dt \right] \\ &= \frac{E_x v_{m,i}}{B_z \omega_{ci}} \left[1 - \frac{1}{2} v_{m,i} \int_0^\infty \left(e^{(i\omega_{ci} - v_{m,i})t} + e^{(-i\omega_{ci} - v_{m,i})t} \right) dt \right] \\ &= \frac{E_x v_{m,i}}{B_z \omega_{ci}} \left[1 + \frac{1}{2} v_{m,i} \left(\frac{1}{i\omega_{ci} - v_{m,i}} + \frac{1}{-i\omega_{ci} - v_{m,i}} \right) \right] \\ &= \frac{E_x v_{m,i}}{B_z \omega_{ci}} \frac{\omega_{ci}^2}{\omega_{ci}^2 + v_{m,i}^2} = \frac{E_x}{B_z} \frac{\omega_{ci}/v_{m,i}}{1 + (\omega_{ci}/v_{m,i})^2} \end{aligned}$$

The solution for \bar{v}_y is analogous, except for $\sin(\alpha) = (1/2i)(e^{i\alpha} - e^{-i\alpha})$.

4.7 The equation of motion for an “average ion” reads

$$m_i v_{m,i} \mathbf{v}_i = e(\mathbf{E} + \mathbf{v}_i \times \mathbf{B}).$$

Introducing the Hall parameter $h = \omega_{ci}/\nu_{m,i}$ and using the usual convention $\mathbf{E} = (E_x, 0, 0)$ and $\mathbf{B} = (0, 0, B_z)$, we have

$$v_{ix} = \mu_i E_x + h v_{iy} \quad \text{and} \quad v_{iy} = -h v_{ix},$$

from which we easily obtain

$$v_{ix} = \frac{\mu_i E_x}{1 + h^2} \quad \text{and} \quad v_{iy} = -\frac{E_x}{B_z} \frac{h^2}{1 + h^2}.$$

4.8 The total current is given by the sum of all partial currents in ring segments $dI \propto n(r)2\pi dr$. Hence, the equivalent density for a parabolic density profile $n(r) = n_0(1 - r^2/a^2)$ becomes

$$\bar{n} = \frac{1}{\pi a^2} 2\pi \int_0^a n(r)r dr = \frac{2n_0}{a^2} \int_0^a \left(r - \frac{r^3}{a^2}\right) dr = \frac{1}{2}n_0.$$

4.9 Ignition occurs, when the α -heating balances the losses by Bremsstrahlung and finite particle confinement time, $P_\alpha = P_{br} + P_H$. Noting that at each DT-reaction one α -particle is generated, we have

$$P_\alpha = \frac{\eta}{1 - \eta} P_{DT} \quad \Rightarrow \quad \frac{\eta}{1 - \eta} = \frac{Q_\alpha}{Q_{DT}} \quad \Rightarrow \quad \eta = 0.154.$$

Problems of Chapter 5

5.1 Start from $H_\phi = I/(2\pi a)$ and $p_{mag} = B^2/(2\mu_0)$. (a) Then

$$p_{mag} = \frac{\mu_0 I^2}{8\pi^2 a^2} = 1.6 \times 10^8 \text{ Pa}.$$

Set 1 atm \approx 1 bar, then $p_{mag} = 1600$ bar. (b) Note that the magnetic pressure has to balance the sum of electron and ion pressure

$$nk_B(T_e + T_i) = 1.6 \times 10^8 \text{ Pa} \quad \rightarrow \quad \frac{k_B T_e}{e} = 500 \text{ V}.$$

The plasma temperature reaches 500 eV in the compressed pinch state.

5.2 $p_{mag} = B^2/(2\mu_0)$ and $\beta = p_{kin}(0)/p_{total}$. Then $B = (2\mu_0\beta^{-1}2nk_B T)^{1/2} = 3.6 \text{ T}$.

5.3 The Alfvén velocity becomes

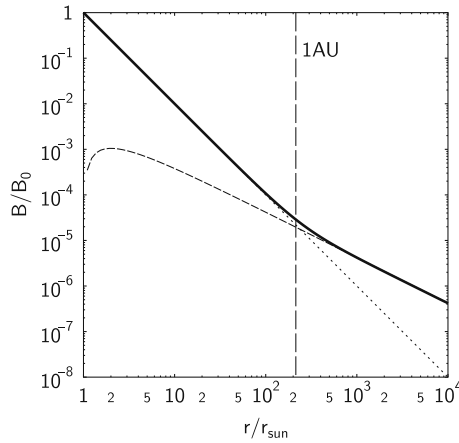
$$v_A = 2.18 \times 10^{16} \text{ m s}^{-1} \frac{3}{\sqrt{2 \times 10^{20}}} = 4.6 \times 10^6 \text{ m s}^{-1}.$$

5.4 The comparison of Alfvén velocity and sound velocity gives

$$v_A = 2.18 \times 10^{16} \text{ m s}^{-1} \frac{3 \times 10^{-5}}{\sqrt{16 \times 10^{12}}} = 1.6 \times 10^5 \text{ m s}^{-1}$$

$$C_s = 9.79 \times 10^3 \sqrt{\frac{0.256 * 4}{16}} \text{ m s}^{-1} = 2.5 \times 10^3 \text{ m s}^{-1}.$$

5.5 Use $\omega_\odot = 2.7 \times 10^{-6} \text{ s}^{-1}$, $r_\odot = 7 \times 10^8 \text{ m}$ and $u_r = 400 \text{ km s}^{-1}$. The figure displays $B(r)/B_0$ (heavy line), B_r/B_0 (dotted line) and B_ϕ/B_0 (short-dashed line). It is found that the magnetic field in the Parker spiral decays $\propto r^{-2}$ for $r < 1 \text{ AU}$ and $\propto r^{-1}$ for $r > 1 \text{ AU}$.



5.6 The total change in magnetic flux is given by the integral

$$\Delta \Phi_m = \int_0^\infty [B_0(r) - B_0] 2\pi r dr$$

$$= 2\pi B_0 \int_0^\infty \left[\left(1 - \frac{2\mu_0 k_B T_e n_0}{B_0^2} e^{-(r/a)^2} \right)^{1/2} - 1 \right] r dr$$

$$\approx -B_0 \pi a^2 n_0 \beta \int_0^\infty x e^{-x^2} dx = -\frac{1}{2} B_0 \pi a^2 n_0 \beta.$$

Problems of Chapter 6

6.1 The phase and group velocities are

$$(a) v_\phi = \frac{\omega}{k} = \frac{\omega_{\text{pi}} \lambda_{\text{De}}}{\sqrt{1 + k^2 \lambda_{\text{De}}^2}} \quad \text{and} \quad v_{\text{gr}} = \frac{d\omega}{dk} = v_\phi \frac{1}{1 + k^2 \lambda_{\text{De}}^2}.$$

(b) For $k^2 \lambda_{\text{De}}^2 \ll 1$, the phase velocity equals the group velocity, $v_\phi \approx v_{\text{gr}}$, and is independent of k . There is no dispersion of waves of different frequency.

6.2 Start from $v_\phi v_{\text{gr}} = c^2$. Then: $\omega d\omega = c^2 k dk$, which after integrating yields $\frac{1}{2} \omega^2 = \frac{1}{2} c^2 k^2 + D$. Since ω is real, $\omega^2 > 0$, hence the integration constant must be positive and can be chosen as $D = \frac{1}{2} c^2 k_0^2 > 0$. Then, $\omega^2 = c^2 (k^2 + k_0^2)$. This means, there can be a cut-off frequency $\omega_{\text{co}} = k_0 c$.

6.3 (a) Start from (6.95) for the refractive index of the R-wave. The ion term can be neglected because of $\omega_{\text{pi}}^2 \ll \omega_{\text{pe}}^2$. In the electron term we use $\omega \ll \omega_{\text{ce}}$ to arrive at

$$\mathcal{N}_{\text{R}} \approx \left(1 + \frac{\omega_{\text{pe}}^2}{\omega \omega_{\text{ce}}} \right)^{1/2},$$

from which the desired limit is obtained when $\omega_{\text{pe}}^2 \gg \omega \omega_{\text{ce}}$. (b) Now, use the definition $\mathcal{N} = kc/\omega$ and solve for ω to arrive at

$$\omega = \frac{k^2 c^2 \omega_{\text{ce}}}{\omega_{\text{pe}}^2} \quad \text{and} \quad \frac{d\omega}{dk} = 2 \frac{\omega}{k}.$$

6.4 Use the definition $n_{\text{co}} = \epsilon_0 m_e \omega^2 / e^2$ and $\omega = 2\pi c / \lambda$ to obtain $n_{\text{co}} = 2.8 \times 10^{27} \text{ m}^{-3}$.

6.5 The cut-off is defined by $\mathcal{N} = 0$. Then we have

$$0 = \mathcal{N}^2 = \epsilon = 1 - \frac{\omega_{\text{pe}}^2}{\omega^2} - \frac{\omega_{\text{pp}}^2}{\omega^2}$$

resulting in $\omega_{\text{co}} = 2^{1/2} \omega_{\text{pe}}$.

6.6 $f_{\text{ce}} = 1.4 \text{ MHz}$, $f_{\text{pe}} = 12.7 \text{ MHz}$, $f_{\text{uh}} = (f_{\text{ce}}^2 + f_{\text{pe}}^2)^{1/2} = 12.8 \text{ MHz}$.

6.7

$$\frac{d\omega}{dk} = \frac{\omega}{k} \Rightarrow \frac{d\omega}{\omega} = \frac{dk}{k} \Rightarrow \ln \omega = \ln k + c \Rightarrow \omega = v_\phi k.$$

Problems of Chapter 7

7.1 Equate the electron retardation current (7.31) with the ion saturation current (7.27) and set $\Phi_p = 0$ for convenience. This balance defines the floating potential Φ_f . Solving for the floating potential and using the quasineutrality of the unperturbed plasma $n_{e0} = n_{i0}$ gives

$$\Phi_f = \frac{k_B T_e}{e} \ln \left[0.61(2\pi)^{1/2} \left(\frac{m_e}{m_i} \right)^{1/2} \right] = \begin{cases} -3.3k_B T_e/e & (\text{H}^+) \\ -5.2k_B T_e/e & (\text{Ar}^+) \end{cases}$$

7.2 The one-dimensional electron current to the probe is

$$j_e = -e \int_{v_{\min}}^{\infty} v_z f(v_z) dv_z \quad \text{and} \quad v_{\min} = \left(\frac{2eU_p}{m_e} \right)^{1/2}.$$

Then the derivative of the probe characteristic can be written as

$$\frac{dj_e}{dU_p} = \frac{dj_e}{dv_{\min}} \frac{dv_{\min}}{dU_p} = +e v_{\min} f(v_{\min}) \frac{e/m_e}{\sqrt{2eU_p/m_e}} = \frac{e^2}{m_e} f[v(U_p)].$$

7.3 Use $U_2 = U_1 + U_p$ to rewrite (7.46) as

$$-I_p = I_{i0} + I_{e0} \exp\left(\frac{e(U_1 - \phi_p)}{k_B T_e}\right) \exp\left(\frac{eU_p}{k_B T_e}\right)$$

Then eliminate the exponential containing $U_2 - \phi_p$ by means of (7.46) yielding

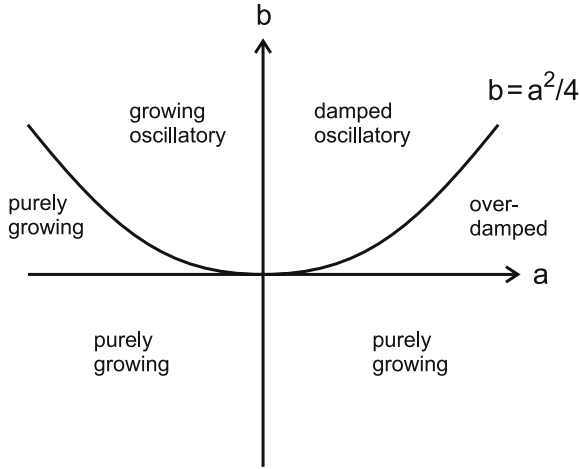
$$-I_p = I_{i0} + (I_p - I_{i0}) \exp\left(\frac{eU_p}{k_B T_e}\right),$$

which by simple rearrangement gives the tanh-shape of the double probe characteristic.

7.4 The slope of the double probe characteristic in the origin is $dI_p/dU_p = eI_{i0}/(2k_B T_e)$. Then a straight line through the origin with this slope intersects the asymptote $I = I_{i0}$ at $U_p = 2k_B T_e/e$.

Problems of Chapter 8

8.1 Set $x = \hat{x} \exp(-i\omega t) = \hat{x} \exp(-i\omega_R t) \exp(\omega_I t)$, which has unstable solutions for $\omega_I > 0$. Overdamped or purely growing modes have $\omega_R = 0$. The characteristic equation for the differential equation then becomes $\omega^2 + i\omega a - b = 0$ with the solution

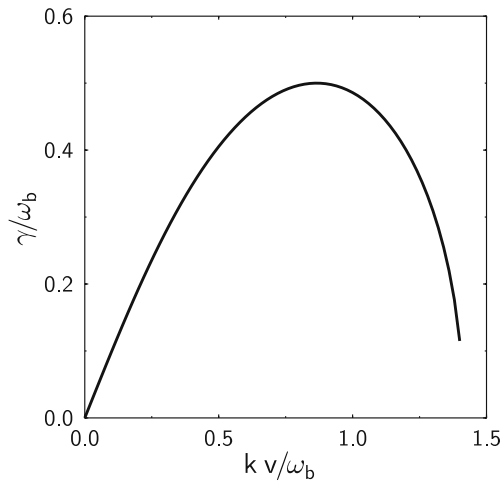


$$\omega_{1,2} = -\frac{i}{2}a \pm \sqrt{b - \frac{a^2}{4}}$$

8.2 The dielectric function reads

$$\epsilon = 1 - \frac{\omega_b^2}{(\omega - kv)^2} - \frac{\omega_b^2}{(\omega + kv)^2},$$

which is equivalent to a quartic equation with real or pairs of complex conjugate roots. The roots are given by



$$\omega = \pm \left[k^2 v^2 + \omega_b^2 \pm \left(\omega_b^4 + 4k^2 v^2 \omega_b^2 \right)^{1/2} \right]^{1/2}.$$

Two of these roots are purely imaginary and the one with positive imaginary part is unstable.

8.3 Insert $\omega = \omega_R + i\omega_I$ in (8.22) and require that the imaginary terms cancel:

$$0 = \omega_I - \frac{\omega_R \omega_I}{|\omega|^4} \omega_{pe} \omega_{pi}^2.$$

Noting that $\omega_R = |\omega| \cos(\theta)$ yields (8.23). Now, set $\omega_I = |\omega| \sin(\theta)$ with $|\omega|$ from (8.23) and calculate $d\omega_I/d\theta = 0$ yielding $\tan(\theta) = \sqrt{3}$ and $\theta = \pi/3$. From $\omega = [\omega_{pi}^2 \omega_{pe} \cos(\theta)]^{1/3} \exp(i\pi/3)$ we obtain (8.24).

Problems of Chapter 9

9.1 Note that the total energy W_{tot} is a constant of motion. Let $g(W_{tot}) = g(\frac{1}{2}mv^2 + q\Phi)$ be the distribution function. Then the Vlasov equation can be written as

$$\frac{dg}{dW_{tot}} \left(\underbrace{\frac{\partial W_{tot}}{\partial t}}_{=0} + v \frac{\partial W_{tot}}{\partial x} - \frac{q}{m} \Phi' \frac{\partial W_{tot}}{\partial v} \right) = \frac{dg}{dW_{tot}} \left(+q\Phi'v - mv \frac{q}{m} \Phi' \right) = 0.$$

9.2

$$\frac{1}{n_{e0}} \int_0^\infty v f_M^{(1)}(v) dv = \left(\frac{m_e}{2\pi k_B T_e} \right)^{1/2} \frac{k_B T_e}{m_e} \int_0^\infty e^{-y} dy = \left(\frac{k_B T_e}{2\pi m_e} \right)^{1/2}.$$

9.3 The integral is of the same type as in the previous problem, but now the lower bound of the integral is $v_c = (2e(\Phi - \Phi_{min})/m)^{1/2}$.

9.4 Follow the advice preceding (9.55).

9.5 The unstable mode has a frequency difference from the plasma frequency given by (8.8). Then the difference between the phase velocity and the beam velocity is

$$v_0 - v_\varphi = \frac{\Delta\omega}{k} = \frac{\omega_{pe}}{k} \frac{1}{2} \left(\frac{\alpha_b}{2} \right)^{1/3}.$$

With $\hat{\Phi}_t = m(v_0 - v_\varphi)^2/4$ and $\omega_{pe}/k = v_0$ we obtain the desired result.

9.6 The trapping condition reads $m\Delta v^2 = 4e\hat{\Phi}$ for a difference between phase velocity and beam velocity $\Delta v = (\omega_{pe} - \omega)/k = \Delta\omega/k$. The fastest growing mode

has $\Delta\omega = 2^{-4/3}\alpha_b^{1/3}\omega_{pe}$. Then the energy density becomes

$$W_E = \frac{\varepsilon_0}{2}\langle E^2 \rangle = \frac{\varepsilon_0}{4}k^2\hat{\Phi}^2 = \frac{\varepsilon_0}{4}k^2\left(\frac{m}{4e}\right)^2\Delta v^4.$$

Eliminating $k = \omega_{pe}/v_0$ and using $\alpha_b = n_b/n_p$ gives the desired result.

Problems of Chapter 10

10.1 The dust charge is $q_d = 4\pi\varepsilon_0a\Phi = 4.45 \times 10^{-18}$ C which is $Z_d = 27.8$. This gives an initial (electric) potential energy $W_{\text{pot}} = 1.78 \times 10^{-17}$ J corresponding to 111 eV. From energy conservation, $W_{\text{pot}} = mgh$, a maximum height of $h = 883$ m is obtained.

10.2 For $P \rightarrow \infty$, (10.25) requires $\eta_f = \eta_c$. Therefore, (10.26) reduces to

$$(\mu\tau)^{-1/2} = e^{-(\eta_f + \tau\eta_c)} \quad \text{or} \quad \eta_f = \frac{1}{2(1 + \tau)} \ln(\mu\tau) = 0.078.$$

The normalized ion density becomes $n_i/n_\infty = e^{\tau\eta_c} = e^{7.8} = 2440$, a tremendously high value, which demonstrates the inadequacy of assuming a Boltzmann response for the ions.

10.3 The electron Debye length is $\lambda_{De} = 410 \mu\text{m}$. At the Bohm velocity $v_B = k_B T_e/m_i$, an ion has the kinetic energy $m_i v_B^2/2 = k_B T_e/2$. The normalized floating potential of a sphere is $e\Phi_f/k_B T_e = 2.41$. The collection radius then becomes

$$b_c = a \left(1 + \frac{2.41 k_B T_e}{0.5 k_B T_e} \right)^{1/2} = 2.41 a = 12.2 \mu\text{m}.$$

The dust charge is $q_d = (1675 \times 5 \times 3)e = 4.03 \times 10^{-15}$ C. This gives a Coulomb radius $r_C = 12 \mu\text{m}$. Because the collection radius is much smaller than the electron Debye length, the ion wind force is dominated by the orbit force. Since the Coulomb radius equals the collection radius, the grazing trajectory touches the grain at the ‘‘midnight’’ position, i.e., exactly opposite to the illumination direction.

10.4 At r_{\min} and for $\dot{r} = 0$ the energy equation (10.53) reads

$$\begin{aligned} \frac{m_i}{2}v_0^2 &= \frac{m_i(m_i v_0 b)^2}{2m_i^2 r_{\min}^2} - \frac{q_d e}{4\pi\varepsilon_0 r_{\min}} \\ 0 &= r_{\min}^2 - b^2 + 2r_{\min}r_C, \end{aligned}$$

which gives the desired result.

10.5 Consider a symmetric displacement of both particles by δr from their equilibrium positions. Expand the restoring force into a Taylor series, which gives a first order term

$$\delta F_r = -m\omega_0^2\delta r - \frac{2q_d^2}{4\pi\epsilon_0 d_0^3}(2\delta r).$$

Using the definition (10.68) for d_0 , we obtain the equation of motion $\delta\ddot{r} + 3\omega_0^2\delta r = 0$, which yields the frequency of the breathing mode $\omega_{br} = \sqrt{3}\omega_0$.

10.6 Define the spring constant D_n for an interaction with a neighbor at distance $n\Delta$. Then,

$$D_n = \frac{q_d^2}{4\pi\epsilon_0 n^3 \Delta^3} (2 + 2n\kappa + n^2\kappa^2) e^{-n\kappa},$$

which gives the desired r.h.s. of the dispersion relation after summing over all pairs of neighbors at $\pm n\Delta$.

10.7 The deflecting force for the i -th particle is given by

$$F_i = F_\Delta \left(\frac{\eta_i - \eta_{i-1}}{\Delta} + \frac{\eta_i - \eta_{i+1}}{\Delta} \right).$$

The distance between particles i and $i + 1$ increases as

$$s = \left[\Delta^2 + (\eta_i - \eta_{i+1})^2 \right]^{1/2} \approx \Delta \left[1 + \frac{1}{2} \left(\frac{\eta_i - \eta_{i+1}}{\Delta} \right)^2 \right],$$

which contains only a second-order correction to Δ that can be neglected. Assuming a wave-like perturbation $\eta(x, t) = \hat{\eta} e^{i(kx - \omega t)}$ we have

$$-\omega^2 m = \frac{F_\Delta}{\Delta} (2 - e^{-ik\Delta} - e^{+ik\Delta}) = \frac{4F_\Delta}{\Delta} \sin^2 \left(\frac{k\Delta}{2} \right),$$

which gives a purely imaginary ω that attains a maximum at $k\Delta/2 = \pi/2$ or $\Delta = \lambda/2$, i.e., a zig-zag arrangement of nearest neighbors.

10.8 The force between infinitely large charged planes is independent of the distance between the planes. Point-like particles in a linear chain interact via a three-dimensional force law, which may be Coulomb or Yukawa and decays as r^{-2} or faster.

Problems of Chapter 11

11.1 A charge in a parallel-plate capacitor causes image charges on the plates. As the charge moves, the image charges change and a displacement current flows in the outer circuit. The exponentially growing electron avalanche generates a current waveform of exponential shape. When the electrons move at a constant drift velocity $v_d = -\mu_e E$, the current rises as $I \propto e^{\alpha v_d t}$. The current is zero again when the last electron has reached the electrode.

11.2 (a) Inserting the separation ansatz into the diffusion equation, and dividing by $R(r)T(t)$, we have

$$\frac{1}{T(t)} \frac{dT(t)}{dt} - \frac{D_a}{R(r)} \left(\frac{d^2 R(r)}{dr^2} + \frac{1}{r} \frac{dR(r)}{dr} \right) = 0.$$

Because each of these two terms is only dependent on t or on r , respectively, the terms must be a constant (with the dimension of a reciprocal time), say $-1/\tau$. Then $T(t) \propto \exp -t/\tau$.

(b) The constancy of the term containing $R(r)$ can be rewritten as

$$\frac{d^2 R}{dr^2} + \frac{1}{r} \frac{dR}{dr} + \frac{R}{D_a \tau} = 0$$

$$\frac{d^2 R}{dx^2} + \frac{1}{x} \frac{dR}{dx} + R = 0, \text{ with } x = r(D_a \tau)^{-1/2}.$$

This is Bessels differential equation for $J_0(x)$.

(c) From $R(a) = 0$ we obtain $2.405 = a(D_a \tau)^{-1/2}$ with the first zero $J_0(2.405) = 0$, and $\tau = D_a^{-1}(a/2.405)^2$.

11.3 Multiplying (11.17) by the applied voltage \hat{U} gives the total current $\hat{I} = \hat{U}/Z_b$ in the two branches. Then the ratio of the current in the capacitor to that in the RL -branch is

$$\frac{\hat{I}_C}{\hat{I}_{R+L}} = \frac{i\omega(v_m + i\omega)}{\omega_{pe}^2},$$

which is a small quantity in the given limit.

11.4 The collisionless skin depth is $\delta_{cl} = c/\omega_{pe}$. At $n_e = 10^{17} \text{ m}^{-3}$ we have $\omega_{pe} = 1.78 \times 10^{10} \text{ s}^{-1}$ and obtain $\delta_{cl} = 0.017 \text{ m}$.

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