1 Introduction

The interaction of charged particles with matter has been an issue of extensive investigations throughout the whole last century. Its theoretical treatment starts with the classical description of the energy loss of fast projectiles considered by Bohr [24]. Later a quantum mechanical treatment of the energy transfer to bound electrons was established by Bethe [18] and refined by Bloch [23]. Further considerable improvements of the theoretical description have been achieved by Fermi and Teller [41] and finally by Lindhard [79]. The present status of the theory has, e.g. been reviewed in the monographs by Sigmund [118, 119]. Till nowadays an enormous number of publications are dedicated to specific questions on the energy loss for a variety of possible projectile and target conditions. Recent applications are the energy transfer to pellets for inertial confinement fusion, electron cooling of heavy ion beams as well as the deceleration of particle beams in traps.

The interaction of a test particle with a medium of charged particles like the stopping of an ion in an electron plasma or its deceleration in a trap can be described in two approaches which are complementary to each other. The dielectric theory (DT) is a continuum theory in which the response of charge and current densities to external perturbations is calculated. While this requires cut–offs at small distances (or large wavenumbers in Fourier space) to exclude hard collisions of close particles, the collectivity of the excitation can be taken into account. In the binary collision approximation (BC), on the other hand, the motion of the ion is described as the aggregate of subsequent pairwise interactions with the target electrons. This requires cut–off parameters at large distances (corresponding to small wave numbers in Fourier space) to account for screening.

For a physically meaningful comparison between DT and BC we adhere in this book to the following terminology: The basic, but generally unobserved quantity in BC is the energy or velocity transfer ΔE_i or Δv_i, respectively, to the test particle in a collision with specific initial data. Averaging with respect to quantities like the phase angle φ of the cyclotron motion and integration with respect to the impact parameter $\boldsymbol{s}$ yields the energy loss $\mathrm{d}E_i/\mathrm{d}l$ of the test particle with monochromatic electrons. Here $\mathrm{d}\boldsymbol{l} = \boldsymbol{v}_i \mathrm{d}t$ is the path element of the test particle moving with velocity $\boldsymbol{v}_i$ in a time interval $\mathrm{d}t$. Then averaging with respect to the electron velocity distribution $f(\boldsymbol{v}_e)$ yields the stopping power S and the stopping force or drag force $\mathcal{F}$,

$$S = -\mathcal{F} \cdot \hat{\boldsymbol{v}}_i = -\frac{\mathrm{d}\mathcal{E}_i}{\mathrm{d}l} = -\left\langle \frac{\mathrm{d}E_i}{\mathrm{d}l} \right\rangle . \tag{1.1}$$

In Chap. 2 we review the previous work on this subject, present the methods which were employed and their results and point out the inherent problems in approximation methods like perturbation expansion and linearization. These are associated with the infinite range of the Coulomb interaction and the role of the collective excitations in the target, large velocity transfers in hard collisions and the transition to a quasi-one-dimensional electron motion for strong magnetic fields. In contrast to the field-free case the BC depends then on the sign of the interaction between the test particle and the electrons. Consider, e.g., a test particle moving parallel to the magnetic field, while the electrons move like beads on a wire along the field lines. In the attractive case no velocity transfer takes place at all, while it is maximal in the repulsive case. This indicates a failure of the perturbation expansion. Even in the attractive case caution is indicated. For small ion velocities the stopping power has the logarithmic behavior typical for one-dimensional problems unless one accounts for the velocity dependence of the lower cut–offs. In any case the validity of the more analytical approaches, perturbation expansion in BC and linearization in DT must be checked by numerical simulations. To this end we employ classical trajectory Monte-Carlo (CTMC) and particle-in-cell (PIC) simulations.

It turns out to be advantageous to include the cut–offs, which are physically motivated by (dynamic) screening and quantum diffraction already on the level of the interaction potentials. For this purpose we have developed analytical methods in which the exact form of the interaction potential must be specified only at the end of the calculation of the stopping power.

This program is carried out in Chap. 3 for the BC. Closed expressions for the averaged energy transfer in second-order perturbation theory are obtained for the limiting cases of weak and strong magnetic fields and for parallel ion motion in arbitrary magnetic fields. The validity of the perturbation expansion and the appearance of chaotic regimes are studied by comparison with CTMC calculations. Knowing the velocity transfers in the binary collisions one can also calculate the velocity diffusion of charged particles in a magnetic field, i.e. the straggling.

In Chap. 4 we turn to the DT, which is formulated in linear response (LR) by calculating first the dielectric function, which involves an integration in velocity space. The zeroes of this function describe the excitation modes of the target. Then the imaginary part of the inverse of the dielectric function is integrated in Fourier space for the stopping power. Closed expressions are obtained in the limits of small and large projectile velocities in a weak as well as in a strong magnetic field. For intermediate fields the stopping power can only be evaluated in closed form under the assumption of weakly interacting electrons with a vanishing plasma frequency. Then the stopping power does not receive any contribution from dynamic collective plasma modes, but the collectivity can be reintroduced by replacing the Coulomb interaction between the ion and the target electrons by a screened interaction. From its very concept this reduced linear response (RLR) should be equivalent to the BC with a screened electron-ion interaction, and such a conformity is verified explicitly. As in the BC there emerges a logarithmic anomalous behavior of the stopping power at low ion velocities and strong magnetic fields both in the LR and the RLR versions of the DT. As the averaging with respect to the electron velocity distribution is done first when calculating the dielectric function this cannot be avoided by employing velocity dependent cut–offs in the later spatial (Fourier) integrations. Insofar the LR is less flexible than the BC.

The velocity dependence of the cut–off at small distances is suggested by quantum diffraction. An ab initio quantum treatment of the stopping power is presented in Chap. 5. This involves the equation of state and the dielectric function of a magnetized quantum plasma and their semiclassical limits. In the framework of the quantum BC the conformity between the RLR and the transition to the classical case are shown.

In Chap. 6 some applications are discussed. Electron cooling is a powerful technique to improve the phase space structure of ion beams in storage rings. In the cooling section the ion beam is superimposed by a comoving electron beam. Due to the acceleration in the electron gun the velocity distribution of the electrons in the rest frame of the beams is highly anisotropic, the temperature parallel to the beam and its magnetic guiding field is lower by some orders of magnitude than the transverse temperature. As the transverse motion of the electrons is quenched by the magnetic field, it is rather small longitudinal velocity of the electrons which sets the scale for the velocity dependence of the stopping power.

Another recent application is the deceleration of heavy ions or antiprotons by electrons in traps for the purpose of precision experiments on QED and symmetries, respectively. Here the particles move under the influence of the external electric and magnetic fields, the mean fields produced by the particles themselves and the drag force $\mathcal{F}$. The stopping of the heavy particles is accompanied by a heating of the electrons, which in turn loose energy by radiation. The solution of the coupled equations yields the time in which the particles come to rest for the precision experiments. For ions the stopping process must be faster than the recombination. This can be achieved under realistic experimental conditions.

To conclude we propose in Chap. 7 a pragmatic approach for a calculation of the stopping power. In the presence of a magnetic field there exist no closed solutions. Even approximate treatments like second order BC or linearized DT can only be evaluated in closed form in certain limiting cases like parallel ion motion, an infinitely strong magnetic field etc. The validity of these approximations is critically examined as there exists no universal parameter of smallness. Unphysical divergences can be suppressed by using physically well motivated velocity dependent cut–off parameters. An explicit comparison with numerical simulation validates the linearization of the DT and the perturbative BC except for a very slow motion of the ions transverse to the magnetic field. Fortunately this region of parameter space is unimportant for the present experiments on ion beam cooling and trapping.

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