General information

The exercise sessions will be held as blackboard sessions, where the participants will present their solutions to the group. As such, the problems should be set up and solved before the session. The focus of the exercises lies on analyzing and discussing the task at hand together with the group: thus, a perfect solution is not required to be awarded points. The (attempted) solutions should be submitted via email to the assistant at the start of the exercise session on March 24th. A point will be awarded for each question, and a person will be chosen to present their solution from the pool.

Exercise 1.
Fusion plasma heating – Pathway to 20 keV

Significant heating is crucial in order to achieve the high temperatures required for magnetic confinement fusion.

a) Explain the physics principles used in the conventional plasma heating methods, including both intrinsic and extrinsic methods.

b) What are their advantages and limitations?

c) How significant are the methods in the existing machines (e.g. JET and ASDEX Upgrade) and in future devices (ITER and DEMO)?

Exercise 2.
Ohmic heating

Ohmic heating is the most basic heating method for tokamaks. It utilizes the resistivity of the plasma by running a current through the plasma. The resistivity is given approximately by the Spitzer resistivity

$$\eta_s = \frac{\pi Z e^2 m_e^{1/2} \ln\Lambda}{(4\pi\epsilon_0)^2 (k_B T)^{3/2}} \approx 15 \times 10^{-4} \times T_{eV}^{-3/2} \Omega\text{m},$$

where temperature is in eV in the last expression.

a) Explain qualitatively why the plasma resistivity drops (and conductivity improves) strongly with increasing plasma temperature ($\eta_s \sim T^{-3/2}$)?

b) Derive the power balance including only transport losses $P_T = 3nT/\tau_E$ and ohmic heating $P_O = \eta j^2$, assuming some current density j, and solve the equilibrium temperature.

c) Assume ITER-like values $a = 2$ m, $I_p = 15$ MA, $n_e = 10^{20}$ m^{-3}, and $\tau = 1$ s and calculate the equilibrium temperature. How does this compare to fusion relevant temperatures?

Exercise 3.
RF heating

As seen from above, Ohmic heating is insufficient to sustain fusion reactions and other means of heating, such as RF heating, are required.

a) Calculate the electron and ion gyrofrequencies (also known as cyclotron frequencies) as a function of the magnetic field B.

b) How is the heat transferred from the injected RF wave to the plasma particles?

c) What are the primary classes of resonances used for RF-heating?

d) What are their characteristic frequencies and why?

e) What is the main application of lower hybrid heating systems?

f) List the various RF-heating methods, and their advantages and limitations.

g) Why does ion cyclotron resonance heating antenna have to be located close to the plasma?

Exercise 4.
Neutral beam heating

a) Why are neutral particles needed for the beam heating of a tokamak plasma?

b) How is the heat transferred from the NBI-particles to the plasma particles?

c) Derive an equation for the intensity of the neutral beam as a function of the distance that the beam travels through a plasma (slide 14 in the “Plasma heating” lecture).

d) Why the neutral beams are sometimes arranged tangentially to the plasma? Can you say something about the possibility to drive plasma current with NBIs?

e) Describe the main components of an NBI-injector.

f) Describe the operation principle of an NBI-injector.

g) What limits the performance of NBI-injectors?

h) What are the main differences between positive and negative NBI-systems?