## 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. 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

$$\eta_s = \frac{\pi Z e^2 m_e^{1/2} \ln \Lambda}{(4\pi\epsilon_0)^2 (k_B T)^{3/2}},$$

where $\ln \Lambda$ is the Coulomb logarithm. In this exercise, assume that $\ln \Lambda \approx 15$ (a reasonable approximation for a fusion-relevant plasma).

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 $P_T = 3nk_BT/\tau_E$ 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 $\tau = 8$ s and calculate the equilibrium temperature. How does this compare to fusion relevant temperatures? For the purposes of this exercise, assume that the current density is constant across the plasma cross section, and that the plasma cross section is approximately circular.

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

b) List the various RF-heating methods, and their characteristic frequencies.

c) What are their main limitations and advantages?

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

e) 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) Why are the neutral beams sometimes arranged tangentially to the plasma? What can you say about the possibility to drive plasma current with NBIs?

d) Describe the main components and operating principle of an NBI-injector.

e) What limits the performance of NBI-injectors?

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