Nuclear Fusion and Plasma Physics **EPFL**
Prof. A. Fasoli SPC
Teachers: Umesh Kumar, Luke Simons *25 November 2024*

Solutions to Problem Set 10

Exercise 1 - The tokamak Scrape-Off Layer

a) The Scrape-Off Layer (SOL) thickness results from a balance between cross-field and parallel dynamics. The number of particles traveling along poloidal field lines in the SOL (and so reaching the divertor) is equal to the number of particles escaping the plasma volume due to cross-field motion.

$$2\pi a(2\pi R_0)\Gamma_r = 2(nc_sL_{SOL}(2\pi R_0))$$

The right-hand side of the equation is multiplied by 2 since the particles traveling parallel to the field touch the material boundary in 2 locations. It follows that:

$$\pi aD\frac{\partial n}{\partial r} = nc_sL_{SOL}$$

Taking $\frac{\partial \mathrm{n}}{\partial \mathrm{r}} \sim \frac{\mathrm{n}}{\mathrm{L_{SOL}}}$ gives:

$$\pi aD\frac{n}{L_{SOL}} = nc_sL_{SOL} \Longrightarrow L_{SOL} \sim \sqrt{\frac{\pi aD}{c_s}}$$

b) Let's evaluate L_{SOL} with ITER parameters.

$$L_{SOL} \sim \sqrt{\frac{\pi aD}{c_s}} \sim \sqrt{\frac{\pi \times 2(m) \times 1(m^2/s)}{8.7 \times 10^5(m/s)}} \sim 0.0027\,\mathrm{m} \sim 2.7\,\mathrm{mm}$$

c) ITER is expected to produce 500 MW of fusion power with a gain factor of $Q = 10$. This means 50 MW of auxiliary heating and 100 MW ($P_f/5$) of alpha heating. In total a power (P_{SOL}) of 150 MW will reach the divertor target if there is no radiation. the power flux q in MW/m^2 at the target assuming no expansion of the SOL thickness is:

$$q = \frac{P_{SOL}(MW)}{Area_{SOL}(m^2)} = \frac{150}{2\pi R_0 L_{SOL}} \sim 1.4\,GW/m^2$$

Exercise 2 - Neutron irradiation damage in ITER and the fusion power plant

a) We will justify with rough calculations that the expected dpa in a fusion power plant will be about 100 times larger than in ITER.
The dpa is the number of displacements per atom caused by neutron irradiation. It is then a function of neutron energy, neutron fluence, and it has some statistical dependence on the material. To simplify the problem we have assumed that ITER and the fusion power plant use the same materials and are both DT-fueled, meaning that the energy of the neutron is the same in the two cases. We define neutron fluence as the number of neutrons per unit area reaching the material surface per year. The neutron fluence is simply proportional to the fusion power, and, given that the other parameters are the same, so is the dpa. We take the fusion power for ITER equal to 500 MW and 1.56 GW for the power plant (corresponding 500 MW of electrical power). The neutron rates are then calculated as the fusion power divided by the energy released during one fusion reaction, E_f:

$$n_{rate} = \frac{P_f}{E_f} \tag{1}$$

which gives for the power plant $n_{rate,PP} = 5.54\ \times 10^{20}$ neutrons/s and for ITER $n_{rate,ITER}$=1.77 $\times 10^{20}$ neutrons/s. To find the value of dpa/year we should multiply theses values by the number of seconds of fusion plasmas per year, which is different for the two, and also divide each value the total internal area of each machine. If we assume that the power plant has the same dimensions as ITER, we should include only the number of seconds per year.

$$\frac{dpa_{PP,year}}{dpa_{ITER,year}} = \frac{n_{rate,PP} \times 300(days/year) \times 20(hours/day) \times 3600(s/hours)}{n_{rate,ITER} \times 150(days/year) \times 1(hour/day) \times 3600(s/hours)} = \frac{1.35 \times 10^{28}}{1.1 \times 10^{26}} \tag{2}$$

It gives:

$$\frac{dpa_{PP,year}}{dpa_{ITER,year}} \sim 122 \tag{3}$$

Notice that the ratio of dpa ended up being the ratio of neutrons per year because of several assumptions:

- we have assumed the same size of the machines thus the same total area
- we assumed the same material as plasma facing component. This helped us to not deal with any nuclear calculations and to take the statistical displacement per atom due to a neutron equal in the two cases
- we assumed they both use DT fuel, this allowed to have the same neutron energy for the two cases

- Finally, using directly the output power helped us to not care about the fusion cross-section, and any other plasma processes taking place inside the reactor, as all is summarized in the expected output power from fusion.

Exercise 3 - Choice of plasma facing component for high heat fluxes surfaces

a) The heat flux q in W/m^2 given by the Fourier equation $q = -k\, dT/dx$ represents the heat transfer rate per unit area in the direction normal to the plasma facing material. The minus sign is the consequence of the fact that heat is transferred in the direction of decreasing temperature. Under steady-state conditions with linear temperature distribution within the substrate, the temperature gradient can be expressed as :

$$\frac{dT}{dx} = \frac{T_2 - T_1}{L} \tag{4}$$

Where L is the thickness of the material T_2 and T_1 respectively the temperatures at the cold and hot side of the substrate.
The heat flux is then:

$$q = -k\, \frac{T_2 - T_1}{L} \tag{5}$$

or

$$q = k\, \frac{\Delta T}{L} \tag{6}$$

To find the maximum heat flux each material would withstand, we need to replace ΔT by its maximum difference temperature ΔT_{max}.

$$q_{max}(W/m^2) = k_{material}(W.m^{-1}.K^{-1})\, \frac{\Delta T_{max,material}(K)}{L(m)} \tag{7}$$

The results of this calculation for each material are written in the table below.

	Iron (Fe)	Tungsten (W)	Beryllium (Be)	Copper (Cu)	Graphite (C)
$T_{melting}$ $(°C)$	1538	3422	1287	1085	3600
ΔT_{max} $(°C)$	513	1141	430	362	2000
k $(W/m/K)$	80	173	200	401	60
q_{max} (MW/m^2)	4.1	19.74	8.6	14.5	12

b) The values computed in the first part of the exercise suggest the materials that have good thermal properties in order to withstand the very high heat fluxes in tokamaks. Other criteria must be taken into account when choosing one of the materials for TCV or ITER. The plasma-facing component not only should have good thermal properties but should also keep the plasma pure to avoid dilution, should minimize the tritium retention and should have a low activation rate due to neutrons. **Tungsten**, as seen in the first part of the exercise would withstand the highest heat flux. Tungsten also has a low sputtering ratio and low tritium retention, thus it would be a good candidate for ITER. We also found that **Graphite** has good thermal properties, it could be used on TCV which does not use DT fuel. **Copper** has a very good thermal conductivity but a limitation in its use is the relatively low melting point.