Control and operations of tokamaks
Exercise Session 10 - Plasma 1D profile evolution with TORAX

Lecturer: F. Felici

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Installing TORAX

This exercise uses TORAX and Jupyter Notebook. For convenience we have packaged all the libraries needed in **torax_exercise10.zip** which can be downloaded and extracted. See the enclosed README for a description of the contents.

If running in the lab there is also a helper script to install and launch the notebook used for the exercise. Double click **run_torax.bat** in the extracted zip to do so. If running on Windows but not in the lab see the README.txt.

Otherwise on Mac/Linux you can follow regular TORAX installation instructions (linked below). (If you are unfamiliar with Git, in place of the Git checkout commands you can use the **torax** and **qlknn-hyper** libraries from the zip file):

- Follow installing TORAX.
- `pip install .[tutorial]`
- `jupyter notebook TORAX_exercise.ipynb`

Background

This exercise focuses on investigating the impact of heating and current drive actuators on q-profile tailoring for the ITER hybrid scenario. Optional questions also cover the impact of radiation on the scenario, and TORAX solver options.

The ITER hybrid scenario is an advanced scenario run at lower current (∼12MA) than the standard baseline scenario (15MA). It can achieve higher plasma beta and relatively high confinement through a combination of avoiding MHD instabilities and reduced turbulence through q-profile tailoring and associated effects.

A baseline TORAX configuration has been provided in the notebook. A convenient modification routine is also provided that solely modifies the config attributes of relevance to this exercise. All simulations in this exercise have the following characteristics:

- Heat, particle, and current diffusion are all simulated
- The simulation has two phases, a current ramp-up phase from 0-100 seconds, starting from 3MA, with a linear rise up to the final current (12.5MA in the baseline simulation). In the nominal case, at 100s, an LH transition occurs and a pedestal forms.
- Temperatures and densities at normalized toroidal coordinate $\hat{\rho} = 0.95$ are imposed. Ion and electron temperatures at $\hat{\rho} = 0.95$ are 0.5 keV in L-mode, and 3 keV in H-mode. The density at normalized toroidal coordinate $\hat{\rho} = 0.95$ is always 0.85 of the Greenwald fraction, which is plasma current dependent; $n_{GW} = I_p/(\pi a^2)$, where n_{GW} is in $10^{20} m^{-3}$, I_p is the plasma current in MA, and a the minor radius in m.
- The QuaLiKiz-neural-network (version QLKNN10D; van de Plassche PoP 2020) is used for turbulent transport. It is a surrogate of the QuaLiKiz physics-based quasilinear gyrokinetic transport model. The primary instability leading to turbulence in the ITER regime is the ion-temperature-gradient (ITG) mode. Among other dependencies, the local critical T_i gradient threshold of the ITG mode increases with s/q, where s is magnetic shear, and q is the q-profile. In addition, regions of negative magnetic shear are highly stabilizing and can lead to internal transport barriers.

- To maintain consistency with an LH transition, it is required to have the total input power exceed 50MW at 100s. This condition however is not checked, but should be kept in mind when configuring your simulations. In reality, the LH transition power threshold has parameter dependencies like plasma density, etc., but for the purpose of this exercise we "set" it as 50MW for all cases.

Exercise 10.1 - Ramping up the current

a) By varying the `Ip` timetrace, investigate the effect of different plasma current ramp rates on the speed of penetration of inductive current, the evolution of the loop voltage profile `Vloop` and the q-profile. Plot and interpret the time evolution of the edge loop voltage `Vloop_LCFS` and the internal inductance `li3`. Compare the different simulations with different `Ip` ramp-up rates. Use the provided `set_LH_transition_time` function for this, whose input argument `LH_transition_time` sets the LH transition time, modifying the plasma current ramp-rate, pedestal formation, and heating triggers, to match, all with the baseline final $I_p = 12.5\ MA$.

b) How can we interpret the difference in `li3` during ramp-up (i.e. what is the cause) and what are the physics consequences? Compare the radial profiles `Vloop`, `q` and `j_total` at the start of the flat-top phase for the different cases, what can you say about the current distribution and stationarity?

Exercise 10.2 - Adjusting heating

a) Returning to the original `Ip` time trace (reaching 12.5MA at 100s), now add 16.5MW of NBI power starting at different times during the ramp-up. Examine the effect on the `Te`, `q` and `j_total` profiles and explain the results. How does the onset of heating impact the time traces of `qmin` and `li3`?

b) Turn off the NBI power during ramp-up. Instead, modify the ECRH power (up to 40MW) and deposition radius (between 0.1-0.6) from 50s onwards and investigate the impact on the q-profile and `Ti`. What kind of q-profiles increase `Ti` and `Q_fusion` during the flattop phase after the LH transition? It is recommended to maintain P_NBI + P_ECRH = 50MW at 100s for a fair Q comparison. How does off-axis ECRH impact the minimum of the q-profile? Can you find a combination of `Ip` and ECRH deposition such that `qmin`>1.5?

Exercise 10.3 - Maximise Q

Maximize Q and avoid MHD! With your new intuition, maximize fusion Q following the LH transition, by a choice of `Ip`, NBI, and ECRH heating, with the following constraints:

- Maintain `q_min` > 1 This avoids sawteeth instabilities which can seed neoclassical tearing modes; neither are currently simulated by TORAX but keep this constraint for the exercise.
- Total power at t=100s must be > 50MW to trigger an LH transition.
- `Ip` cannot exceed 18MA during the current rampup. (Note that the current ramp does not need to be monotonic.)

Exercise 10.4 - Compare solver methods (optional)

Compare the Newton-Raphson and predictor-corrector (linear) TORAX solver methods. Which is faster and why? Explore the number of predictor-corrector steps needed for the predictor-corrector method to approximate the more rigorous Newton-Raphson method.

Exercise 10.5 - Turn on radiation (optional)

Turn on radiation. What happens when including no heating during the ramp-up phase, and why? Explore the trends when changing `Zeff`, and increasing the tungsten content.