Control and operations of tokamaks
Exercise Session 8 - Plasma 1D profile evolution

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Before doing the exercise you can familiarize yourself with the RAPTOR code by doing a few tutorials.

- Download the `RAPTOR_exercise.zip` file and unpack it.
- Navigate to the demos folder and run `echodemo RAPTOR_tutorial_1_introduction.m`, or step through the file in the MATLAB GUI.
- Do the same for tutorials 2, 3 and 4.

Open `exercises/RAPTOR_exercise_1.m` the same way and do the exercises listed below.

1 Exercises

1. By varying the I_p trace in $U(1,:)$, investigate the effect of different plasma current ramp rates on the speed of penetration of inductive current, the evolution of the loop voltage profile U_{pl} and the q profile. Note: adjust correspondingly the linear density ramp, such that the maximum density is reached when I_p reaches 12MA. Plot and interpret the time evolution of the edge loop voltage `out.upl(end,:)` and the internal inductance `out.li3`. Compare the different simulations (with different I_p ramp-up rates) in a plot with I_p on the x-axis and the internal inductance $l_{i,3}$ on the y-axis. How can we interpret the difference in $l_{i,3}$ during ramp-up (i.e. what is the cause) and what are the physics consequences? Compare the radial profiles upl, q and j_{par} at the start of the flat-top phase for the different cases, what can you say about the current distribution and stationarity?

2. Returning to the original I_p time trace (reaching 12MA at 100s), now use $U(5,:)$ to add 16.5MW of NBI power starting at different times during the ramp-up. Examine the effect on the T_e, q and j_{par} profiles and explain the results. How does the

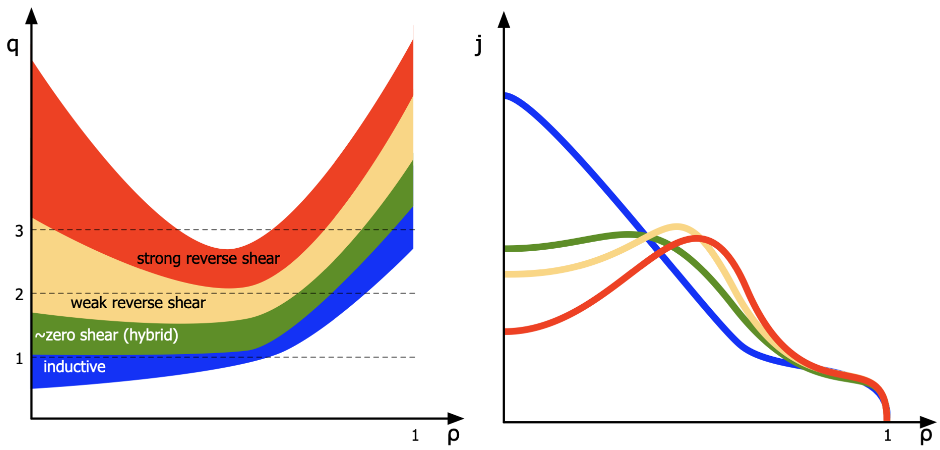

Figure 1: Typical ranges of q profiles and corresponding typical parallel current density profiles for different tokamak scenarios

onset of heating impact the time trace `out.jpar(1,:)` (current density on-axis)? Explore how transiently negative magnetic shear during the ramp-up can cause the creation of an internal transport barrier (the effect can be highlighted by comparing simulations with `params.chi_e.aitb` respectively to 0 and 1).

3. Use $U(5,:)$ to add 33MW from 50s onwards and the $U(2:4,:)$ from 75s to add at 20MW of EC By turning on the various entries $U(2:4,:)$, consider respectively:

   (a) as on-axis pure heating ($U(2,:)$)

   (b) as off-axis co-ECCD at `rhodep = 0.3` ($U(3,:)$)

   (c) as off-axis co-ECCD at `rhodep = 0.4` ($U(4,:)$)

   Investigate how off-axis ECCD leads to a transport barrier at the start of flat-top (100s) by causing a reversed-shear q profile. How does off-axis ECCD impact the minimum of the q profile? Can you adjust off-axis deposition radius `params.echcd.rdep(3)` such that $q_{min} > 1.5$?

4. Find a combination of timing for heating and current drive to keep q_{min} above 1 for as long as possible.

5. (Optional.) Explain the size of the initial x_0 and output state $\mathrm{x}(t)$ (`simres.X`). Can you reconstruct the profiles of $\psi(\rho,t)$ and $T_e(\rho,t)$ from $\mathrm{x}(t)$ directly? Use the spline matrices Λ_α (`Lam` / `Lamgauss`) contained in `model.psi` and `model.te`, then compare your results with the profiles given in `out`.

In an nutshell

1.1 Heat diffusivity in RAPTOR

A simple ad-hoc formula for the evaluation of electron heat diffusivity χ_e is used in this exercise. This formula takes into account the experimental observations of enhanced energy confinement for higher plasma current and for negative magnetic shear $s = \frac{\rho}{q}\frac{\partial q}{\partial \rho}$:

$$\chi_e = \chi_{neo} + \underbrace{c_{ano}\rho \mathrm{q} F(s) T_{e0}[keV]^{c_{T_e}}}_{\chi_{anomalous}} + \chi_{central} e^{-\rho^2/\delta_0^2} \tag{1}$$

with

$$F(s) = a_{ic}/[1 + e^{w_{ic}(d_{ic}-s)}] + (1 - a_{ic}) \tag{2}$$

You can see it consists of three terms: (1) a small neoclassical contribution; (2) an anomalous contribution; (3) a gaussian diffusion term in the center to reproduce the experimental observation of profile flattening. Within $\chi_{anomalous}$, a shear-dependent factor $F(s)$ is included, to be able to include the effect of improved confinement for negative magnetic shear. This factor can be disabled by setting $a_{ic} = 0$, or added by setting $a_{ic} = 1$. The additional factor $T_{e0}[keV]^{c_{T_e}}$ was added later to the anomalous diffusion term, to capture the degradation of confinement for increased input power. This exponent can be loosely related to the power degradation exponent in confinement scaling laws.

Tailoring the q profile is one of the main things we would like to do in order to reach a given confinement scenario. Figure 1 below summarise some relevant q profiles found in literature. Scenarios with reversed shear and/or transport barriers are referred to as advanced scenarios, typically having a high non-inductive current fraction of more than 50%. In this exercise, we propose you to generate an ITB by tailoring a reversed-shear profile.

1.2 Finite elements representation

The PDEs for $\psi(\rho, t)$ and $T_e(\rho, t)$ are transformed into finite-dimensional ODEs by projecting onto a set of n_{sp} cubic splines Λ_α:

$$\mathbf{x}(t) = \begin{bmatrix} \hat{\boldsymbol{\psi}}(t) \\ \hat{\mathbf{T}}_{\mathbf{e,i}}(t) \end{bmatrix}, \qquad \begin{bmatrix} \boldsymbol{\psi}(\rho, t) \\ \mathbf{T}_{\mathbf{e,i}}(\rho, \mathbf{t}) \end{bmatrix} = \sum_{\alpha=1}^{n_{sp}} \Lambda_\alpha(\rho) \begin{bmatrix} \hat{\boldsymbol{\psi}}(t) \\ \hat{\mathbf{T}}_{\mathbf{e,i}}(t) \end{bmatrix}, \tag{3}$$

This finite element decomposition has the advantage of reducing the order of spatial derivatives required in the computation, through integration by parts.