Optimizing fusion: avoidance of runaways

The international effort to develop fusion energy is on the threshold of a new era: two fusion devices with **net energy gain** are under construction with planned start of operation by 2025, SPARC (a compact high-magnetic field device at MIT, USA) and ITER (a reactor-scale device in France).

The safe operation of fusion devices is critical for the success of the fusion program. Design of operating conditions and magnetic configurations, is key. However, only a small part of the parameter space is accessible to physical experiments. This necessitates numerical searches for better designs.

In this project we will focus on finding designs for the avoidance of ***runaway electrons***, which can be generated in events causing a disruption of the operation, when a part of the current running in the plasma is converted to a beam of relativistic electrons. Such beams can damage the wall of the device, and need to be either avoided by a reliable control of the plasma discharge, or mitigated by injecting material or inducing magnetic perturbations. There are many degrees of freedom to consider: when and what mixture of materials to inject, the spectrum of magnetic perturbations to impose, etc.

Building on decades of experience in the field, the Plasma Theory group has developed a comprehensive numerical solver that simulates the generation and dynamics of runaway electrons in disruptions. The solver, DREAM} (*Disruption Runaway Electron Analysis Model*), computes the runaway electron distribution function self-consistently with the plasma density, temperature, and electric field evolution [2]. The inputs to DREAM are the initial profiles of the currents, densities and temperatures; magnetic geometry; transport coefficients; the electrical properties of the wall; as well as the sources of injected impurities. In simplified terms, DREAM is a function transforming the input parameters to the electron distribution function, from which the key functionals, such as the runaway current and energy spectrum, can be calculated. DREAM can also be operated in a less computationally expensive fluid mode, where runaway electrons are treated by semi-analytical source terms of electrons moving with the speed of light For the purposes of this project we will focus on the runaway current evolution, and therefore using the fluid version of DREAM is sufficient. If time allows, the obtained results can be corroborated by kinetic simulations.

Optimisation In order to design safe and reliable operating scenarios for next-generation fusion devices, advanced simulations are needed. Self-consistent simulations that take into account the evolution of plasma parameters across the entire plasma are, however, computationally expensive. Thus, conventional optimisation based on such simulations would be a monumental task, even using High Performance Computing (HPC), due to the "curse of dimensionality" implied by the high-dimensional parameter space.

The aim of this project is to construct an optimization framework that can use DREAM to determine the regions in parameter space where runaways can be avoided.

1. Read the initial part (until chapter 3.4) the MSc thesis by Vallhagen et al Disruption mitigation in tokamaks with shattered pellet injection to get an overview of disruptions and runaway phenomena. Note, that unlike the Vallhagen thesis, this project is not focused on disruption mitigation via material injection and, in particular, no pellet dynamics will be included. Here, the focus lies on finding suitable optimization methods. However, the effect of impurity atoms is important in all disruptions, even those without material injection.

2. To get comfortable with using DREAM, first reproduce a case that corresponds to the figures of the left column of `https://ft.nephy.chalmers.se/~pusztai/APS2021_Pusztai_poster.pdf` by using the input files provided by Istvan.

3. Decide, in discussion with supervisors, what control parameters should be used for the optimization. These can include

    - geometric parameters (ellipticity, triangularity, toroidicity),
    - plasma composition (density of hydrogen isotopes and impurities coming from the wall)
    - magnetic perturbation strength (and its radial variation),
    - initial current density profile,
    - initial density and temperature profiles,
    - details of the cooling process (in the exp-decay case the time-constant and final temperature),
    - electrical properties of the conducting wall

4. Select an optimization method (consult supervisors).

5. Define the metric for the performance of the scenario: final runaway current, conducted thermal losses (minimize the heat to the wall) and current quench time.

6. Perform optimization across the domain of physically realistic values of the control parameters. There might be multiple local optima; assess the sensitivities of these to uncertainties in the control parameters.

7. (**Optional, depending on previous progress*) Use kinetic simulations to corroborate the obtained results (isotropic, superthermal or fully kinetic).

8. (**Optional, depending on previous progress*) Optimize regarding the density, timing and species of injected material (hydrogen, deuterium or noble gases). For this part the shattered pellet injection modules are best suited.

The total duration of a MSc project is approximately 20 weeks (full time) – the above project has been written assuming two collaborating students. The work could be divided in several ways, for example one student could be mainly responsible for the computational part (e.g. writing the optimization framework), and the other could mainly focus on the physics (e.g. performing and benchmarking of Dream simulations).

In addition to the research detailed above, the students will need to write a thesis detailing the work conducted during this project. The writing is expected to take at least 5 weeks (full time) of the allotted 20 from each student. This should be distributed during the full duration of the project (continuous documentation of the results), but naturally the writing part will be most intense toward the end.

The examiner is Tünde Fülöp and the supervisors are István Pusztai and Oskar Vallhagen, in collaboration with Patrik Jansson and Nick Smallbone from CSE (Dept of Computer Science and Engineering). Close collaboration with the author of the Dream code, Mathias Hoppe, is foreseen.

In the meantime another project based on Dream will be conducted by Aaro Järvinen from he Finnish Advanced Computing Hub. Aaro is focused on using Bayesian methods to connect inputs and outputs of Dream with the aim of allowing for easier validation to experimental data. Although Aaro's project is not about optimization, the students may benefit from interaction with him as well.

References

[1] Vallhagen et al, *JPP* **86** (2020) 475860401

[2] Hoppe et al, *CPC* **268** (2021) 108098