Projects in plasma physics 2021

Extracting energy from fusion reactions requires heating a mixture of hydrogen isotopes to temperatures of the order of 100 million kelvin (at which the gases are ionised, forming a plasma), while maintaining a sufficiently high density. The principal focus of fusion research is on confining and controlling toroidal plasmas with magnetic fields.

Since charged particles follow magnetic field lines, they can be well confined in a ring-shaped magnetic cage with twisted magnetic fields. The magnetic confinement concept which has so far produced the highest fusion performance is the tokamak, where the toroidal part of the magnetic field is produced by coils external to the plasma, while the poloidal part of the magnetic field is generated by an electric current that flows in the plasma.

Runaway electrons One of the most crucial problems facing next generation magnetic confinement devices of the tokamak type is the occurrence of plasma-terminating disruptions. In a tokamak disruption, a sudden loss of stability leads to the release of stored thermal energy to the surrounding structures. The temperature of the plasma facing material is raised, leading to a release of impurities. Due to the influx of impurities from the edge, a quick cooling of the plasma takes place, which impedes current drive. As a result, there is a dramatic rise in the toroidal electric field. These strong electric fields can detach a fraction of the electrons from the bulk plasma and accelerate them to very high energies. The detached electrons are referred to as *runaway electrons*. The beam of runaways can potentially cause severe damage to vital parts of the confinement device. This represents an intolerable risk for large fusion devices like ITER and need to be avoided by a reliable control of the plasma discharge. A good understanding and modelling capacity of runaway electrons will aid in finding ways of controlling them.

Modelling tools 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 numerical solver, DREAM (*Disruption Runaway Electron Analysis Model*)[1], computes the runaway electron distribution function self-consistently with the plasma density and temperature evolution, as well as electric field evolution. The inputs to DREAM are the initial profiles of the currents, densities and temperatures of electrons and ions; magnetic geometry and field configuration; advection and diffusion coefficients; the geometry and electrical properties of the outer wall; as well as the sources of injected impurities. We have also developed a *synthetic radiation diagnostic* tool SOFT that simulates the radiation emitted by a population of relativistic electrons.

The projects described in the following are based on using and further developing these numerical tools.

1 Effect of toroidicity on runaway generation

Tools: DREAM
Skills: Python, LaTeX

Runaway electron generation has conventionally been studied primarily in homogeneous plasmas. Such plasmas are far from representative for actual tokamak plasmas. Although homogeneous plasma models are expected to work well for understanding the fundamental principles of various runaway electron generation mechanisms, to obtain quantitatively correct results the effect of inhomogeneity (e.g. toroidicity, elongation, triangularity) needs to be taken into account. With DREAM, we should now be able to study how runaway electron generation occurs in actual tokamak geometries, and the aim of this project is to specifically study that effect on two of the most fundamental runaway mechanisms: Dreicer and avalanche.

1. Modify the DREAM "runaway" example to use tokamak geometry.
2. Vary the elongation κ, triangularity δ, and Shafranov shift Δ of the magnetic field separately, and study their effect on
   (a) the Dreicer generation
   (b) the avalanche multiplication
3. Compare to previous results, primarily [3, 4].

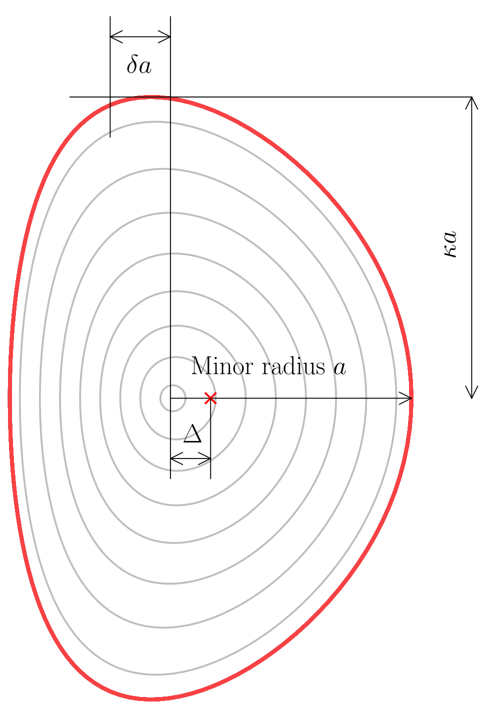

Figure 1: Tokamak cross section illustrating three of the main parameters used to control the shape of a tokamak magnetic field: elongation κ, triangularity δ, and Shafranov shift Δ. The plasma minor radius is denoted a.

2 Analytical magnetic field in Soft

Tools: Soft
Skills: C++, Python

One very powerful way of measuring the properties of runaway electrons in experiments is to record camera images and videos of the electromagnetic radiation they emit. Due to their high energy, runaway electrons emit so called *synchrotron radiation*, which can typically be observed using regular visible-light cameras. An important property of synchrotron radiation is that it is emitted almost exactly along the velocity vectors of the electrons, and so in order for the radiation from an electron to be detected by an observer, the electron must be travelling directly towards the observer. This results in peculiar light patterns being observed, as illustrated in figure 2. At Chalmers, we have developed the synthetic synchrotron diagnostic tool Soft [5, 6] for simulating such light patterns from relativistic electrons.

One of the main applications of Soft is as a post-processing tool for simulations made with Dream. Electron distribution functions calculated with Dream can be given as input to Soft, which calculates the corresponding synchrotron emission patterns. Dream implements an interesting analytical model for the tokamak magnetic field, which contains three shaping parameters. In this project, the same magnetic field model will be implemented in Soft to allow simulations to be made more consistent. The project requires the appropriate expressions for the magnetic field to be derived and implemented into Soft. Preferably, a parameter scan in the three shaping parameters should also be conducted in Soft once the implementation is finished.

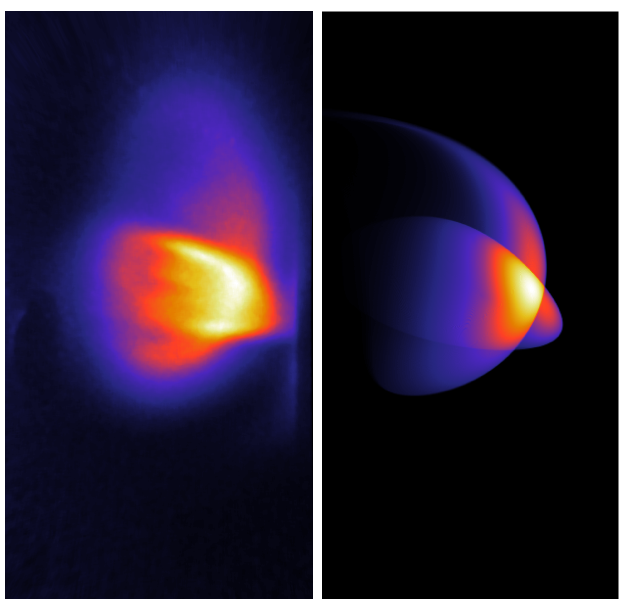

Figure 2: (Left) Camera image from the TCV tokamak, showing a peculiar pattern of synchrotron radiation emitted by runaway electrons. (Right) Corresponding simulation from Soft.

References

[1] O. Embreus and M. Hoppe, `https://github.com/chalmersplasmatheory/DREAM`

[2] M. Hoppe *et al.*, Submitted to Comp. Phys. Comm. (2021).

[3] L.-G. Eriksson and P. Helander, Computer Phys. Communications **154** 175 (2003)

[4] E. Nilsson *et al.*, Plasma Phys. Control. Fusion **57** 095006 (2015).

[5] M. Hoppe, `https://github.com/hoppe93/SOFT`

[6] M. Hoppe *et al.*, Nucl. Fusion **58** 026032 (2018).