Kinetic modelling and validation of flat-top runaway electrons in the TCV tokamak

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Background Runaway electrons pose one of the greatest risks to future fusion reactors of the tokamak type. If control is lost of a runaway beam, it can collide with the tokamak wall and cause severe melting of wall components. Aside from requiring the components to be replaced, which in itself is expensive, the maintenance could require the reactor to be shut down for months at a time, causing costs to sky-rocket and make commercial fusion unfeasible.

One of the primary research focuses in our group at Chalmers has been to understand the dynamics of runaway electrons—how they are generated and how they can be dissipated. While our models are now quite advanced and mature, they have yet to be validated experimentally. With very recent data from the *Tokamak à Configuration Variable* (TCV), located in Lausanne, Switzerland, it should now be possible to validate some of the fundamental properties of our models.

Runaway electrons Our group has a long history of studying the dynamics of runaway electrons. Runaway electrons can occur due to a peculiar property of plasmas: the collisional friction force experienced by a fast plasma particle is inversely proportional to the speed of the particle squared, $F \sim 1/v^2$. Since electrons have a very small mass, they are more easily accelerated, and so in the presence of a sufficiently strong electric field, very energetic electrons can be generated, since there slowing-down force (essentially) decreases the more energetic the particle becomes.

During the past 5 years, we have a developed a kinetic model for studying the behaviour of runaway electrons in homogeneous magnetic fields, which is implemented in the CODE [1, 2] kinetic solver. The kinetic model accounts for various effects, including ion-electron and electron-electron collisions, synchrotron and bremsstrahlung radiation reaction as well as partial screening of ion impurities, just to mention a few features. With this tool, we should be able to study fundamental aspects of runaway electrons in tokamak plasmas, and better understand how we can prevent runaways from at all appearing in tokamaks.

Experimental validation Studying runaway electrons experimentally can be rather difficult. Few diagnostics are capable of providing reliable signals for runaways, and often one has to rely on high-level moments of the distribution function—such as the total plasma current—which are generally very insensitive to the details of the distribution function. One diagnostic technique that has proven very powerful for studying runaway electrons is to measure the synchrotron radiation that they emit. Synchrotron radiation is emitted with a continuous spectrum, ranging from visible up to infra-red wavelengths, and can as such be observed using regular visible-light and IR cameras. In contrast to most other diagnostic signals, the synchrotron radiation tends to be very sensitive to the details

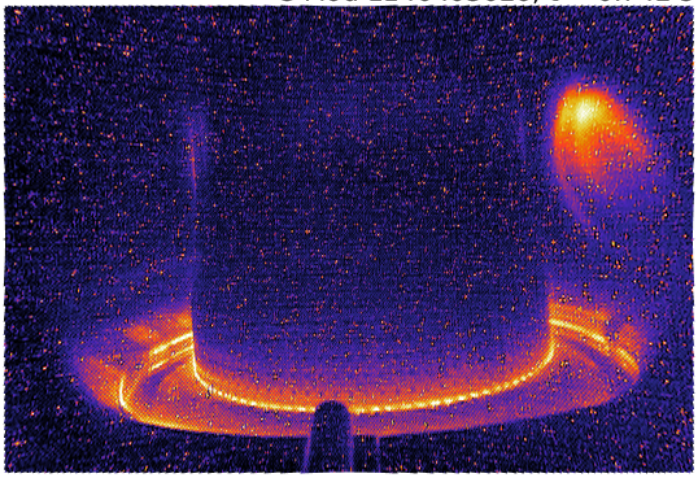

Figure 1: A synchrotron camera image from the Alcator C-Mod tokamak, located at MIT in the USA until its closing in 2016. The comet-like synchrotron spot can be seen on the right side of the image and is here observed with a visible-light camera. Note that the image is false-colour, and in reality the synchrotron spot would be entirely white.

of the distribution function, and therefore provides a direct method for experimentally verifying the dynamics that our runaway models predict.

Synchrotron radiation Synchrotron radiation is emitted by relativistic charged particles when they undergo circular acceleration. Electrons in a plasma are always accelerated in this manner due to the Lorentz force, which forces the electrons to move in helical orbits which follow magnetic field lines. Since runaway electrons usually reach energies which can be several (tens of) times above their rest mass, runaways therefore always emit synchrotron radiation.

An important property of synchrotron radiation is that, due to relativistic effects, it is emitted almost exclusively along the electron velocity vector. For an observer to see the radiation, the electron must therefore be moving towards the observer. This gives rise to strongly asymmetric and quite spectacular radiation patterns in camera images (see for example Fig. 1). Recently, a synthetic diagnostic tool named SOFT was developed by our group and is now widely used around the world to simulate the synchrotron radiation produced by runaway electrons.

Aim The aim of this project is to run simulations using the kinetic simulation code CODE for TCV experimental scenarios in order to obtain runaway electron momentum distribution functions. Once these are obtained, the synthetic diagnostic SOFT should be applied to the distribution functions to compute the expected diagnostic signals produced by these distribution functions. The results should be compared to available experimental data and conclusions about the validity of the kinetic models drawn.

Research plan

The following steps represent the baseline of the project which is expected to fit the time-range of a 7.5 hp project work.

Kinetic modelling

1. Learn about the runaway phenomenon in plasmas by reading the PhD thesis of Ola Embréus [4]. To learn about how the code CODE works, the student should go through the paper by Landreman et al (2014) [1].

2. Obtain a copy of CODE and run basic runaway electron simulations, progressively applying the following effects to the simulations:

   - Electric field (primary/Dreicer) acceleration
   - Synchrotron radiation reaction
   - Secondary (avalanche) generation

3. Retrieve relevant plasma parameters from the TCV experiment database (density, temperature, electric/magnetic field strength etc.) and run CODE with the data.

Once kinetic simulations are done, it is time to calculate the corresponding synchrotron radiation. The initial stages of this part can be conducted in parallel with steps in the kinetic modelling part:

Synchrotron modelling

1. Learn about synchrotron radiation from runaway electrons by reading the licentiate thesis of Mathias Hoppe [5].

2. Obtain a copy of SOFT and run basic synchrotron radiation simulations.

3. Retrieve magnetic equilibrium data from the TCV experiment database and run SOFT for these equilibria.

4. Run SOFT with the distribution functions obtained in the *kinetic modelling* part of the project and compare the results to experimentally obtained synchrotron radiation images.

Relevant TCV discharges to consider are primarily 64593, 64614, 64711 and 64717.

References

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[2] A. Stahl, O. Embréus, G. Papp, M. Landreman and T. Fülöp, "Kinetic modelling of runaway electrons in dynamic scenarios". *Nucl. Fusion* **56** (11), 112009 (2016).

[3] M. Hoppe, O. Embréus, R. A. Tinguely, R. S. Granetz, A. Stahl and T. Fülöp, "SOFT: a synthetic synchrotron diagnostic for runaway electrons". *Nucl. Fusion* **58** (2), 026032 (2018).

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