Estimation of energy and number of runway electrons produced during a GOLEM discharge

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Runaway electrons are high energy particles that appear in tokamaks under certain conditions - e.g. in case of low plasma density. These particles are highly undesirable during normal operation as they can damage important components of the device. Therefore it is of crucial importance to study the generation and losses of these particles in plasmas of smaller devices and use the results to secure safe operation of ITER and future large reactors. During the tasks described below you will become familiar with the conditions suitable for generation of these fast particles in tokamak Golem and you will use one of the most common detectors (Scintillation detector) to study how many of the runaway particles are generated during the plasma discharge.

1 What are Runaway Electrons?

As was mentioned above, runaway electrons are just the electrons in a plasma that have reached high velocities and may be further accelerated by the electric field that is naturally present in the tokamak.

1.1 Electric field in the tokamak

As you probably already know, a significant part of the tokamak principle is similar to the principle of an electrical transformer, thus there is the toroidal electric field that drives the plasma current. The field is necessary for the tokamak to work but on the other hand it can cause problems. The acceleration in the electric field has to be balanced by particle collisions for all particles in order to have a thermal plasma. If it is not balanced, then runaway electrons appear.

1.2 Coulomb drag force and particle velocity

To take a closer look at the Coulomb friction force (due to collisions), see Figure 1 - the 'drag function' peaks at the thermal velocity and drops quickly as v^{-2} for the faster electrons, the electric accelerating force is independent on the velocity, therefore it can be represented as a line parallel to the velocity axis. What are the relations of these two curves to the basic plasma parameters and discharge characteristics? Well, the magnitude of the electric field E moves the horizontal line up and down, the electron density n_e of the plasma scales the curve and the electron temperature T_e moves the peak along the velocity axis. These three parameters are the most important and we can define some critical values using them:

- The Dreicer field as the field in which all electrons run away

$$E_D = \frac{n_e e^3}{4\pi\epsilon_0^2 k T_e} \ln\Lambda \tag{1}$$

- The critical field as the minimal electric field required for RE to appear

$$E_c = \frac{n e^3}{4\pi\epsilon_0^2 m_e c^2} \ln\Lambda. \tag{2}$$

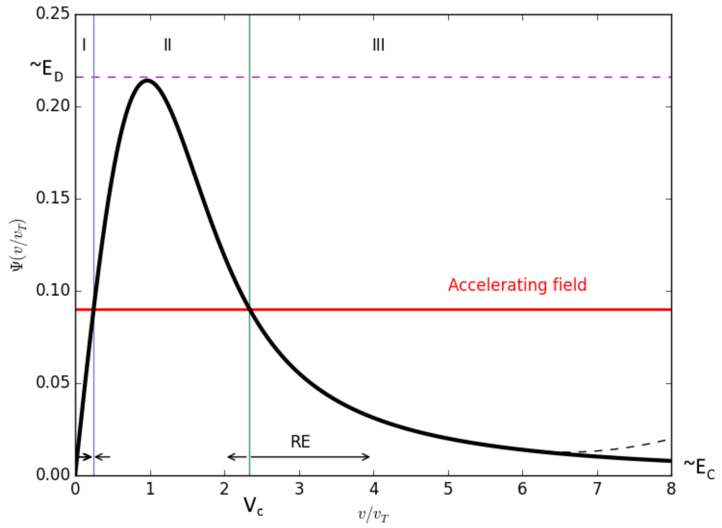

Figure 1: The dependence of the Coulomb friction force on the velocity. The runaway region is on the right.

- The critical velocity as the minimal velocity required for the electron to become a runaway electron

$$v_c = \sqrt{\frac{ne^3}{4\pi\epsilon_0^2 m_e E}\ln\Lambda}. \tag{3}$$

In all relations e, k, c, ϵ and m_e are well known constants and $ln\Lambda$ is the Coulomb logarithm - very weak function of plasma parameters usually close to 15 in fusion plasmas.

2 Detection method

It is very difficult - and in Golem almost impossible - to detect a small number of runaway electrons in the plasma, thus the best option is to focus on their interaction with atoms of limiters and the vessel in general (producing bremsstrahlung radiation and line emission). Every particle with energy in the order of hundreds of keV creates photons of very high energy (hard X-ray, but the energy may be deep in the gamma region, it is not called gamma radiation just because it is not created in the nucleus) when it hits a high density material. Using this knowledge we can easily measure whether a significant number of runaway electrons was created. All runaways hit the wall sooner or later due to drifts or magnetic field imperfections and perturbations. To detect the HXR radiation we use a scintillation detector based on the NaI(Tl) crystal and classic high voltage photo-multiplier (PMT).

2.1 Principles of scintillation detector

In the scintillation crystal the HXR photon is transformed to the shower of low energy photons (usually in the visible range) as it excites the atoms of the material. The shower of photons is then transformed in the photocathode to the shower of electrons which is amplified on the cascade of dynodes to create a measurable current/voltage signal. The height of the voltage peak is directly proportional to the incident photon energy. Our PMT is in the current (continuous) regime.

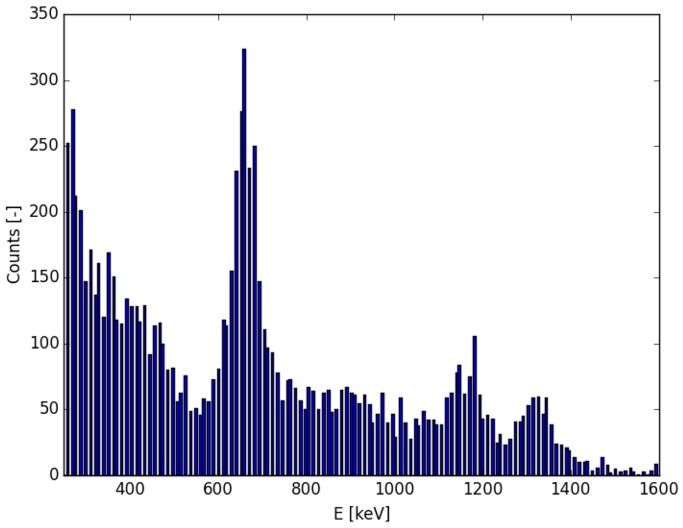

Figure 2: Spectrum of ^{137}Cs + ^{60}Co radioactive sources measured via NaI(Tl) scintillation detector used at Golem.

2.2 Calibration of the detector

The calibration of the HXR scintillation detector in energy was done with the help of gamma radiating isotopes ^{60}Co and ^{137}Cs. The gamma quanta generated by the nuclear transitions correspond to energies 1.1732 MeV and 1.3325 MeV for ^{60}Co and 662 keV for ^{137}Cs. The three full absorption peaks are obvious in the spectrum in Figure 2. According to the voltage of the power source that we will use, the voltage signal of the ^{137}Cs full absorption peak will be

$$U_{Cs}[V] = \exp(0.011 * (U_{PS}[V] - 789.4)). \tag{4}$$

This can give us an estimate of the HXR (RE) energy. Details will be specified during the experiments.

3 Tasks

3.1 A bit of Theory: Acceleration of electrons in the vacuum and how many of them may become runaways in a Maxwellian plasma

a) First task will be a little bit theoretical. Try to estimate the energy that would **electrons achieve in a betatron** (electron accelerator with stable electron orbits) with the **loop voltage values of typical Golem discharge**, e.g. 8 V on the time scale of 10 ms. The electric field is in the first approach the loop voltage divided by the length of the magentic axis

$$E = \frac{U_{loop}}{2\pi R_0} \tag{5}$$

In fact very low density tokamak operation is not far from the operation of an electron accelerator, however the acceleration of runaway electrons is still slower compared to better vacuum conditions of the betatron. Express the energy in various units (eV, Joules). Once finished you can apply your formula or integrator on the loop voltage data from the discharges of the task 2. Assume that the RE are **created at the moment of breakdown**.

Hint: Don't forget about Albert!

b) Having a knowledge of the three important parameters (n_e, T_e, E_ϕ) and assuming nice Maxwellian plasma (we are very theoretical right now :)) try to estimate the fraction of runaway electrons in the plasma (n_{RE}/n_e) and the current they can carry using a simple relation $j_{RE} = en_{RE}c$. Derive the general formula first, then use typical Golem numbers.
Hint: Remember critical velocity as the limit.

3.2 Lets run a density scan and detect some runaways

One of the parameters that are **easy to steer on Golem** is the **pressure of the working gas** in the chamber before the discharge. Given good vacuum conditions, this should be directly proportional to the electron density n_e which is in turn the important parameter affecting runaway electron generation. Therefore we will do a scan in this parameter, 5 discharges with pressures 3,5,10,15,20 mPa would be optimal. The values of the capacitor bank voltage for toroidal magnetic field and Current drive and the timing will be fixed. For each discharge calculate average value of E_c and analyse the signal of the HXR detector, especially these parameters: **time** t_{start} when the first HXR peaks appear after the breakdown, **size of several clear single peaks** I_{HXR} (hopefully we can find some of them), **number of peaks** N and the value of the **integrated signal** over the whole discharge S. For the first two quantities you can use standard MATLAB plot with zooming, the third one can be obtained using the *findpeaks* function, and the last one is just a sum of the signal values. Present the results in a suitable form (graphs, tables).

3.3 Bonus task - try to correctly compare the simple theory and measured values

Try to compare the measured data with the theoretically calculated values, i.e. the energy of the photon from the peak height using Cs calibration data compared to the energy of a electron accelerated in the vacuum and given field. In case of an isotropic spatial distribution of the HXR photons and assuming one electron = one HXR photon, use the knowledge of the detector position (will be specified) and N to estimate the overall number of RE lost to the limiter. How does this cope with the RE fraction of the Maxwellian plasma derived in 1b)? For this you will need also the volume of the Golem plasma. Given the mass of the scintillation crystal calculate the dose absorbed by the crystal during one discharge (use S and the transformation to deposited energy that will be supplied).