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Introduction

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1. Theory basement of runaway electrons(RE)

RE may appear in tokamaks in case of high toroidal electric field and low collision frequency. If a drag force directly connected with a collision frequency ($\boldsymbol{F}_d = m_e\, \boldsymbol{v}\, \nu_{coll}(v)$) is not enough to balance an electric force ($F_e = |eE|$), the electric force accelerates the electrons to tremendous velocity, much higher than the thermal one. For such type of electrons the collision frequency may be written like:

$$\nu_{coll}(v) \ = \frac{e^4 n_e ln\Lambda}{4\pi\varepsilon_0^2 m_e^2 v^3}\left(2+Z_{eff}\right)$$

Where m_e– the electron mass, v – the electron velocity and n_e – the electron density, $ln\Lambda$ – the Coulomb logarithm, ε_0 – the vacuum permittivity and $Z_{eff} = \sum_i \frac{n_i Z_i^2}{n_e}$ – the effective charge. And the final form of the expression for the drag force is:

$$F_d = \frac{e^4 n_e ln\Lambda}{4\pi\varepsilon_0^2 m_e v^2}\left(2+Z_{eff}\right) \sim \frac{1}{v^2}$$

So, small tokamaks with high loop voltage and low electron density, like GOLEM, are the perfect devices for Runaway Electrons studies.

1.1 Generation of Runaway Electrons

1.1.1 Dreicer mechanism

The first description of RE generation was created in 1960s by Dreicer [*H. Dreicer. Electron and Ion Runaway in a Fully Ionized Gas. I. Physical Review, 115(2):238–249, 1959*], [*H. Dreicer. Electron and Ion Runaway in a Fully Ionized Gas. II. Physical Review, 117(2):329–342,* *1960*]. Dreicer considered cylindrical, homogeneous, infinite, fully ionised quasi-steady-state plasma in en electric field with Maxwellian distribution function of electrons.

The equations above make it possible to describe the critical electron velocity required for RE appearance.

$$F_d = F_e$$

$$v_{cr} = \sqrt{\frac{e^3 n_e ln\Lambda\left(2+Z_{eff}\right)}{4\pi\varepsilon_0^2 m_e E}}$$

If electron reaches this threshold velocity the electric force cannot be compensated by the drag force more and the electron continuing acceleration in the electric field becomes “runaway”. Also sometimes is useful to use the initial energy of RE instead of the critical velocity:

$$W_c[keV] = \frac{m_e v_{cr}^2}{2} = \frac{e^3 n_e ln\Lambda\left(2+Z_{eff}\right)}{8\pi\varepsilon_0^2 E}$$
$$\approx 2.2\left(2+Z_{eff}\right)\frac{n_e\left[10^{-19}m^{-3}\right]}{E\left[\frac{V}{m}\right]}$$

This primary mechanism of RE generation is called Dreicer Mechanism; according to it electrons accelerated from a tail of distribution function are getting replaced by electrons from the bulk plasma through diffusion in velocity space. So the population of RE is growing in time.

However the expressions above are written only for electrons with $v_e \gg v_{th}$, for electrons with thermal velocities the collision frequency has no dependence on velocity, so the drag force is proportional to velocity and such mechanism cannot work. Consequently despite the growth of RE population their part is still exponentially small.

1.1.2 Hot-tail mechanism

The second mechanism is named hot-tail mechanism. This mechanism becomes very important for large tokamaks, like JET, TFTR and others. Such devices usually are operated with high electron density and low toroidal electric field, in other words they have perfect conditions to avoid RE. However, in case of disruptions the plasma current extremely grows in the last moments of plasma existing. This growth is directly connected with generation of RE and Dreicer mechanism cannot be used here for explaining this phenomena.

The new mechanism is connected with stages of disruption; the first one is the rapid cooling of plasma, so-called thermal quench. For the fastest electrons the drag force is too low (because of dependence on velocity) to thermalise quickly. But cooling of the bulk plasma leads to increasing of the plasma resistivity and to the second part of disruption – the current quench, decreasing of the plasma current. Consequently the loop voltage grows and hot electrons from the distribution function tail cross the threshold and become RE increasing the plasma current.

1.1.3 Avalanche mechanism

Both of aforementioned mechanisms are named primary mechanisms. These mechanisms describe acceleration of thermal electrons. The next one mechanism is connected with iterations between electrons from runaway region and the bulk plasma.

Despite the collision frequency is decreasing with growth of electron energy collisions are still possible and high energy RE are able to transfer enough energy to the thermal electrons to throw them into the runaway area. This effect is described by Rosenbluth and Putvinski [ссылка] can be expressed in the next equation:

$$\frac{dn_{RE}}{dt} = \frac{I_p}{I_A ln\Lambda}.$$

Here I_p is the plasma current, I_A is the Alfven current. This mechanism describing exponential growth of RE is called secondary mechanism or avalanche mechanism.

1.2 Widespread diagnostics of RE

There are several possibilities for RE measurement, mainly they are connected with radiation from plasma generated by RE. This radiation can be separated into two parts according to the frequency: microwave radiation and radiation in HXR or SXR region. The diagnostics for these types of radiation have significant differences in construction and physical principles.

1.2.1 X-ray diagnostics

The X-ray radiation sources from RE can be separated in 2 types.

The first of them is bremstrahlung – the consequence of the Coulomb interaction of high energy RE with the bulk plasma. Usually this radiation is in the SXP range, diagnostics of bremsstrahlung are the most wide spread for RE observation.

The second one type of X-ray source, so-called “lost RE” is connected with collision of RE with plasma facing components. In such interactions RE lose all energy, so this radiation usually is much more energetic and lies in the HXR range.

The X-ray radiation can be detected by several ways. The first and the most widespread of them is direct measurement with semiconductor detectors. Semiconductor detectors are able to measure the current initiated by the passing high energy particles or X-rays. The detector consists of two semiconductors of different types; such configuration with electric field leads to the situation described by fig. X

Figure X

Charge carriers of different types in the electric field move in opposite directions creating the energy gap on the boundary of semiconductors, so there is no possibility for the electric current. However the interaction with high energy photons (or particles) can give electrons enough energy to “jump” this gap and consequently create the current through the detector.

So, semiconductors give an opportunity to detect photons by measuring the electric current in the detector, which is directly connected with a number of photons or particles on it. The additional construction elements (like foils on detector or matrixes of directional detectors) can also allow getting more resolution in energy and space. However the direct measurement by semiconductor detectors is possible only for SXR and visible light, the more energetic photons have not enough probability of interaction and also they are able to damage the detector.

The second type of diagnostic is a scintillator, this diagnostic measures the secondary radiation generated by Cherenkov Effect. The Cherenkov radiation appears if high energy particles pass through material and usually it is visible light, so such type of measuring is much simpler than direct measurements of high energy particles by semiconductor detectors.

1.2.2 Microwave diagnostics

References