Nuclear Fusion Workshop

EXPERIMENT REPORT

Estimation of Energy and Number of Runway Electrons

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ABSTRACT

In this report, you will have opportunity to read about a phenomena of runaway electrons. The report consists of the theoretical and the experimental part. My task was:

1) Estimation of order of magnitude of the energy and the velocity of the runaway electrons

2) Making the graphs of U_{loop} (loop voltage), n_e (density of electron), HXR (Hard-X-Ray emission of photon) and I_P (current of plasma) with time evolution

3) Analyzing HXR signal, regarding to parameters like t_{start} (starting time), I_{HXR} (size of single peaks), N (number of peaks) and S (integrated signal over the whole discharge)

4) Estimation of critical velocity v_C, critical electric field E_C and Dreicer field E_D

5) To find dependence of $N(n_e)$ and $S(n_e)$, where n_e is the electron density and to discuss their connections.

I have done these tasks in `MATLAB'. In the Results you can see the graphs from my own shot #22452 in the first four tasks and the combination of the shots for the fifth task.

The main conclusions from this experiment are:

- Theoretically calculated energy of electron is three time bigger than the detected signal. This means that all energy is not converted to HXR and it is not easy to predict the real energy of an electron
- The detection of the HXR peaks comes very early after the breakdown, due to the fast acceleration of the electrons and a poor confinement
- With controlling the parameters like n_e (electron density), T_e (electron temperature) and E (toroidal electric field) we can control critical velocity, critical electric field and Dreicer field that are crucial for the existence of the runaways

I would like to thank to Ondřej Ficker for the mentorship, as well as to Darko Lukić and Jelena Prodanović, from my team, for the collaboration and team work, and of course to all people from FEN (Fusion Educated Network) for the great organization of the workshop.

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INTRODUCTION

Nowadays there are many challenges in the realm of energy production. Nuclear fusion seems to be one of the best ways to ensure the desired electric energy to the rapidly growing world. It is a production of clean energy, but it is very difficult to fulfill conditions for a stable process. There are a lot of instabilities, which are hard to predict, as well as high energy particles that can damage important components of the device. One of the most common kinds of high energy particles are the “Runaway electrons”. During a normal operation of tokamak, these particles are highly undesirable. Therefore, it is of crucial importance to understand generation and losses of these particles in order to secure a safe operation of a reactor.

The basic theoretical concepts

Runaway electrons appear when the collisional drag cannot compensate the acceleration force from the electric field. The electric field is generated by Faraday’s Law in a similar way like in a transformer. Electrons hit the wall afterwards, but the ‘runaway’ means that they run away in the velocity, because they are much faster that the rest of the electrons. The expected trajectory of electrons is shown in (Figure 1).

Expected trajectory of runaway electrons

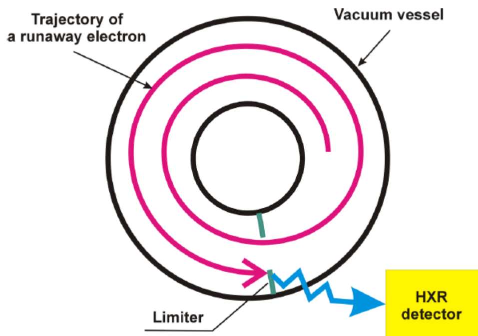

Figure 1.

To become runaway electrons, they must overcome the critical velocity :

$$v_c = \sqrt{\frac{ne^3}{4\pi\varepsilon_0^2 m_e c^2}\ln\Lambda} \tag{1}$$

The critical, as the minimal electric required for RE to appear:

$$E_c = \frac{ne^3}{4\pi\varepsilon_0^2 m_e c^2}\ln\Lambda \tag{2}$$

The electric field, called Dreicer field, in which all electrons run away:

$$E_D = \frac{ne^3}{4\pi\varepsilon_0^2 kT_e}\ln\Lambda \tag{3}$$

In all relations e, k, c, ε and m_e are well known constants of electrical charge, Boltzmann’s constant, speed of light, permittivity of vacuum and mass of an electron. lnΛ is the Coulomb logarithm - very weak function of plasma parameters usually close to 15 in fusion plasmas. In Figure 2 is shown dependence of the Coulomb friction force and velocity. From this graphic we can see how the electric field E and Coulomb friction determine the condition for runaway electrons. The most important parameters that can define some critical values are E, n_e, T_e. 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.

The dependence of the Coulomb friction force on the velocity

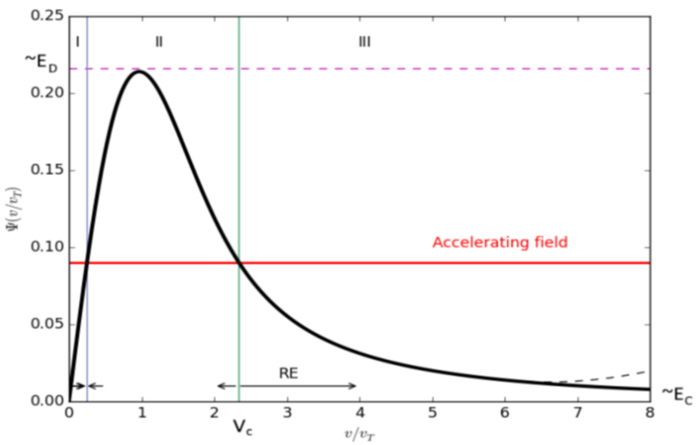

Figure 2.

In this experiment we will measure the number of runaway electrons and their energies. Also we will try to estimate order of magnitude for the critical velocity, the critical electric field and Dreicer field. Sooner or later all runaways hit the wall, due to drifts and perturbations, usually creating photons in hard X-ray (HXR) part of spectrum. To detect this radiation we use a scintillation detector based on the NaI(Tl) crystal and high voltage photo-multiplier (Figure 3). It is usually set on the limiter, because we expect that most of electrons will hit there.

Scheme of Scintillator Detector

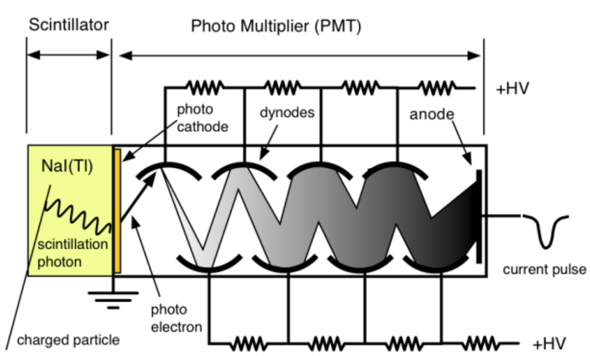

Figure 3.

Spectrum of ^{60}Co and ^{137}Cs

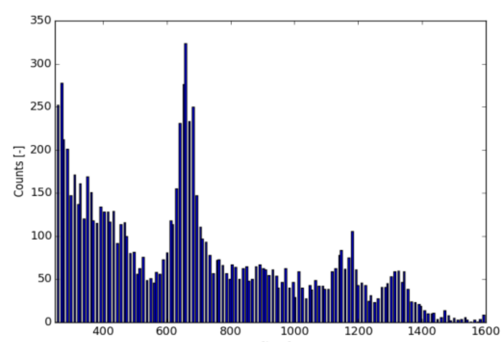

Figure 4.

When high energetic electron changes direction or velocity, it radiates energy, due to bremsstrahlung radiation, creating a HXR photon. With passing through the crystal HXR-photon is converted to a shower of visible or UV photons. Subsequently these photons are converted to the electrons on a photocathode and amplified by successive electrodes, or more precisely dynodes. At the end of a photo-multiplier is a detector, which detects the signal.

To calibrate HXR scintillation we use gamma radiation of isotopes ^{60}Co and ^{137}Cs, which produce energies of 1.1732 MeV or 1.3325 MeV for Cobalt and 662 keV for Cesium. Spectrum of these radioactive sources is shown in Figure 4. All three peaks, that can be seen, are the full absorption peaks. This means that the crystal received all of the HXR photons energy. The energy versus the voltage curve is linear in this expected energy region. Thus one peak is enough to calibrate a scintillation detector. This will give us an estimation of energy of runaway electrons.

We will first estimate theoretically energy of an electron and then compare it with detected and calibrated HXR signal. Our task is also to analyze the HXR signal and find t_{start} (time when the first peak appears after the breakdown), size of several clear single peaks I_{HXR}, numbers of all peaks N and the value of the integrated signal over the whole discharge S. We will do this by using Matlab. Also it is important to assess the critical values for the electron velocity, the electric field and Dreicer field to make complete picture of the `runaways' phenomena. In the end we will find dependency: $N(n_e)$ and $S(n_e)$, where n_e is electron density, and present it on graph. These relations will help us to understand better behavior runaway electron.

EXPERIMENTAL PROCEDURE AND ANALYSIS METHOD DESCRIPTION

The first step in our experiment is to set the parameters. In case of Golem you can change Toroidal magnetic field by U_B, current drive by U_{CD}, gas pressure p_{WG}, working gas (H_2 or He), time delay – T_{CD}, and finally you can turn on the electron gun (Figure 5). To get the perfect shoot you need to balance all of the parameters, which is not easy.

Basic engineering scheme

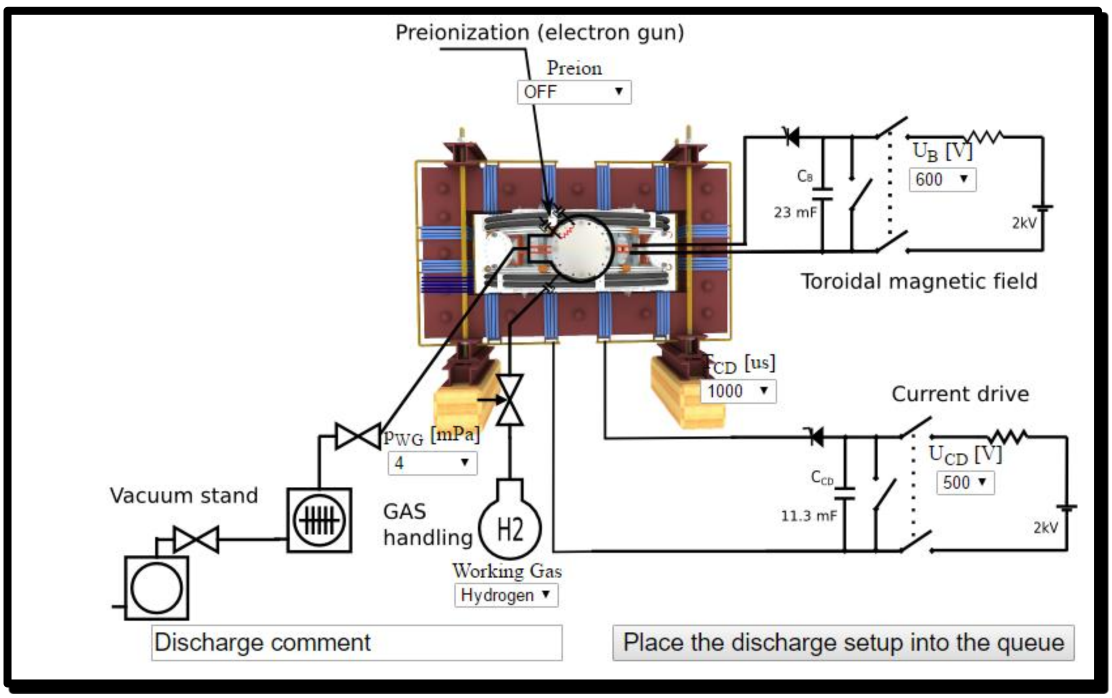

Figure 5.

1) Our first task is to estimate the energy of electrons in a betatron (electron accelerator with stable electron orbits). The betatron is very close to a tokamak with zero plasma density. We will assume it's voltage as the loop voltage of typical GOLEM discharge. To do this, we should get electric field from the following formula:

$$E = \frac{U_{loop}}{2\pi R_0} \tag{4}$$

E is a variable that represents the electric field, U_{loop} is loop-voltage and R_0 =0.4[m] is the major radius of the torus. Now we will use Newton-Euler algorithm (steps 5, 6, 7) to calculate the velocity of an electron.

$$\tilde{E} = \frac{Q\Delta t}{m_0}E \tag{5}$$

Q=$1.6 \cdot 10^{-19}$[C] is electrical charge of electron, Δt=10^{-6}[s] is sample time, m_0=$9.1\cdot10^{-31}$[kg] is the rest mass of electron, and $\tilde{E}$ is a velocity increment due to the acceleration by the electric force. With this iterative process, point by point, we can make a graph of the velocity, thereby creating a graph of the energy.

$$U_{n+1} = U_n + \tilde{E}, \qquad U_0=0 \tag{6}$$

$$v_{n+1} = \frac{U_{n+1}}{\sqrt{1+U_{n+1}^2/c^2}} \tag{7}$$

In equation (6), U_n is an extra variable and in (7), c=$2.9\cdot10^8$ $[\frac{m}{s}]$, which is of course speed of light.

Finally, by using the velocity of electron, we can estimate its energy. It is important to emphasize that particles are relativistic and we must have that on our mind. By putting equation (9) in equation (8) we will get the equation for energy:

$$\varepsilon = c\sqrt{m_0^2c^2 + p^2} \tag{8}$$

$$p = \frac{m_0\, v}{\sqrt{1-\frac{v^2}{c^2}}} \tag{9}$$

This is energy of an electron. To evaluate total energy, it is necessary to multiple calculated energy with the number of all electrons.

It is always good to check equations with a simple assumption: $\lim_{t\to\infty} v = c$, when E=const≠0.

2) Our second task is to show time dependent parameters: U_{loop}(t), n_e(t), HXR(t), I_c(t) and to discuss their connections. We will simply download the data from Golem database and plot graphics. Their connections we will discuss later in Results.

3) Our third task is to analyze data from HXR signal and find parameters like: t_{start}(starting time), I_{HXR}(size of single peaks), N(number of peaks) and S(integrated signal over the whole discharge).

t_{START} (starting time)

This is the time that is passed from the breakdown to the first peak detection. We can simply estimate t_{START} directly from the graph.

I_{HXR} (size of single peaks)

To find single peaks we will zoom the graph of HXR, which will be shown in the second task, and estimate their size. Individual spikes represent energy of the HXR photons, resulting from impact of a high energy with the limiter. From their amplitudes we can calculate their energy, thanks to calibration with isotope Cs. The HXR signal can be calibrated by equation (10).

$$U_{CS} = \exp(0.011 \cdot (U_{PS}[V] - 789.4V)) \tag{10}$$

For U_{PS}=640V, which is voltage on the PMT power source, voltage signal is U_{CS}=0.193V. This value correspond to energy of the full absorption peak E_{AP}, which is 662keV. Now we should use simple proportion (11) to evaluate calibrated values.

$$HXR_{calibrated}[eV] : E_{AP}[eV] = HXR[V] : U_{CS}[V] \tag{11}$$

N (number of peaks)

Number of peaks represent number of electrons, which radiate photons. To estimate this number, we must eliminate the noise first. Noise can add small new peaks on original signal, which can lead us to the wrong conclusion. To avoid that, we use combination of smooth function and another algorithm in order to choose only right peaks. We should be careful with this smoothing functions, because they usually change the original. To get the coordinates of all peaks we use function in Matlab:

```
[hxrPeakValue, hxrPeakIndex] =
findpeaks(hxrData,'MINPEAKHEIGHT',0.004,'THRESHOLD',0.003);    (12)
```

[hxrPeakValue, hxrPeakIndex] represents x and y coordinate of all peaks by matrix, which is the return value of function findpeaks.

`hxrData` is signal from the scintillator and `'MINPEAKHEIGHT'` and `'THRESHOLD'` are parameters, which make difference between real and false peaks. Now we just need to count number of points in matrix `[hxrPeakValue, hxrPeakIndex]` by following instruction :

```
N = numel(hxrPeakIndex)                                  (13)
```

S (integrated signal over the whole discharge)

We can calculate S simply by summing the all timesteps of the data from the signal `hxrData`, because it is represented by the matrix of indexes and values.

```
S = sum(hxrData)                                         (14)
```

Finally we have estimation of energy of all electrons that hit the detector. It is important to emphasize that energy that we predict could be much greater than detected energy. This could happen because electrons radiate in HXR spectrum not only in the direction of the detector but in all directions. Also, all energy of electrons is not converted into HXR radiation.

4) Our fourth task is to estimate order of magnitude for the critical velocity, critical electric filed and Dreicer filed. There are three important parameters (n_e, T, E) that we have to assume. From equation (4), electric field E is proportional to U_{loop}, so we can just estimate average value of U_{loop}. We will use graphs from second task to do this. We can also estimate average value of electron density and temperature from theirs graphs. Finally, we will put our estimated value in equations (1, 2 and 3) from beginning and finish our task.

5) In our fifth task is to show on graph dependence between N (number of runaways) and n_e (electron density). We will do this for 5 succeeded shot and try to find rule. The same procedure we will repeat to find dependence between integrated HXR signal S and also electron density n_e.

RESULTS

1) Estimation of the energy of electron and their velocity

In Figure 6 there are three graphs that represent smoothed loop voltage U_{loop}, velocity of electron during the discharge v and energy of electron E, in function of time t. On the first graph we used smooth function to find easier peaks. The first peak represents breakdown and the last represents end of shot. Between these peaks plasma exists.

Estimation of energy and velocity of electrons

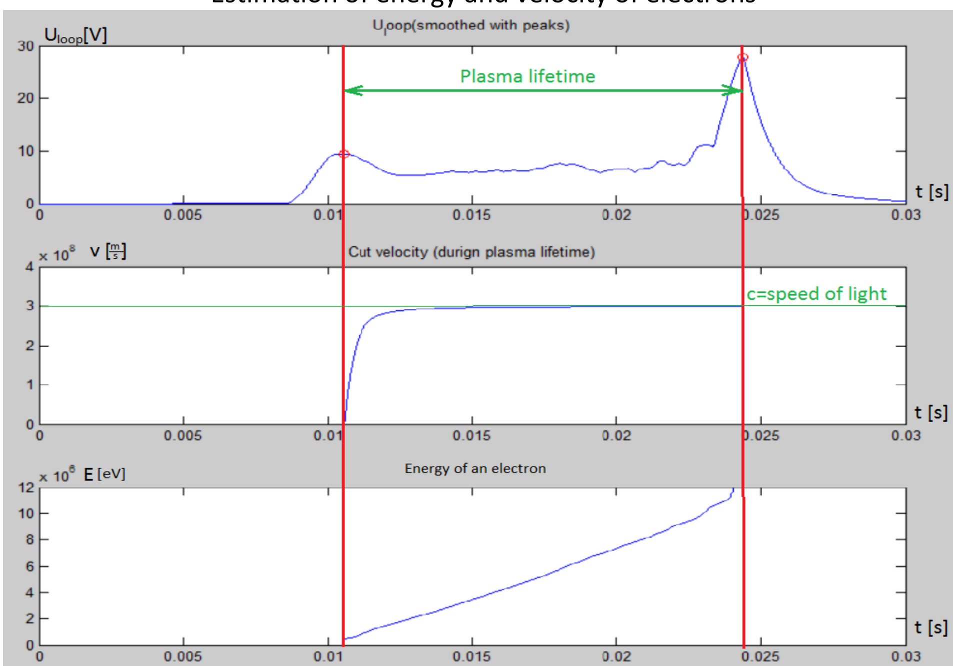

Figure 6.

Checking of assumption : $\lim_{t\to\infty} v = c$, when E=const≠0 (Figure 7)

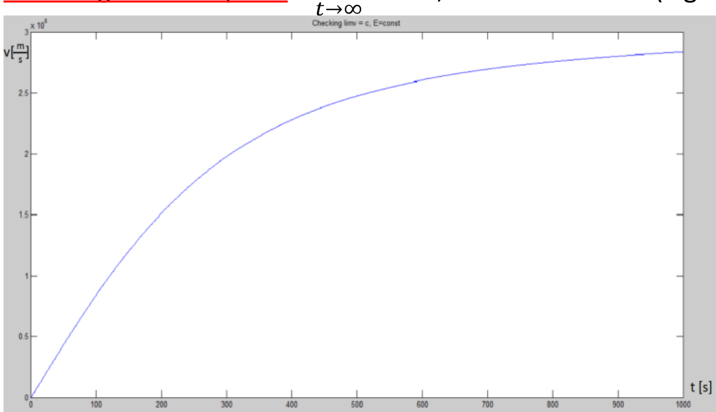

Figure 7.

As we can see velocity of electron approaches the speed of light with the passage of time. This means that we didn't make rough mistake in our calculations.

2) Graphs of U_{loop}(t), n_e(t), HXR(t), T(t), I_c(t)

In Figure 8 we can see that the electron density and the temperature increase with little delay in compare with U_{loop}. Also the peaks of HXR signal are mostly concentrated right after the breakdown, which has happened in 0,0105s. The reason for this is very fast growth of the velocity of electron from Figure 6 and thus appearance of runaway electrons. One more reason for the shape of HXR signal is a strong drift in the magnetic field, wherefore they lose their energy and decelerate. In the graph of temperature 1eV=11 598.53K and in HXR signal 1 a.u.= 3.27MeV.

Graphs of U_{loop}(t), n_e(t), T(t), HXR(t)

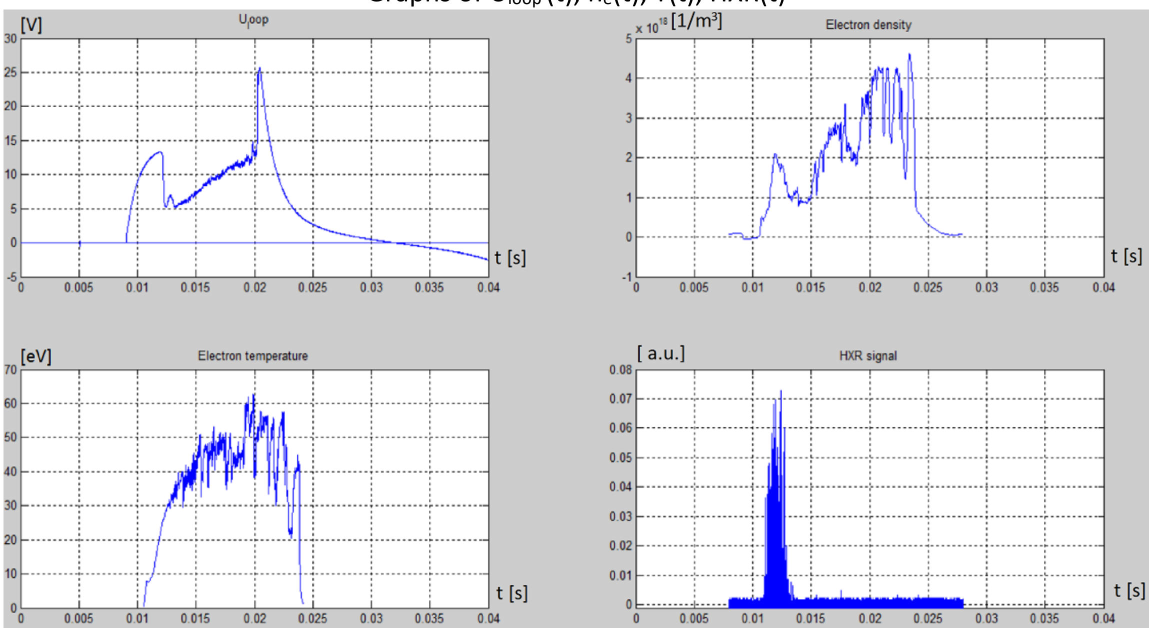

Figure 8.

The plasma current is shown in Figure 9. The growth starts just after the breakdown and shape of the graph is similar to the graph of temperature and density.

Graph of the plasma current

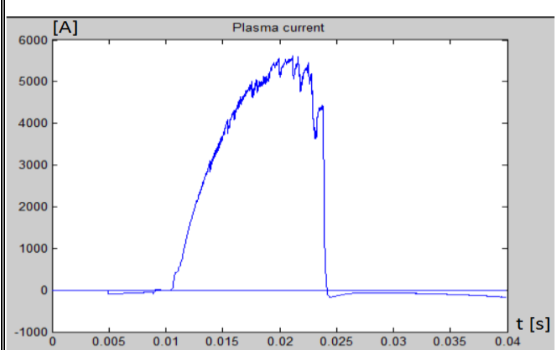

Figure 9.

One more interesting thing is unusually large current. This happens because of the great conductance of plasma. As the temperature of heated plasma rises, the resistance decreases. In systems like this, plasma current can reach few millions ampere, how it should be reached in the ITER.

3) Analysis of parameters of HXR signal

t_{START} (starting time)

We can simply estimate this parameter directly from the graph (Figure 10).

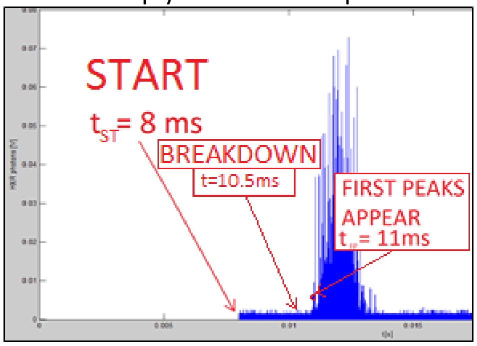

Figure 10.

$$t_{START} = t_{FP} - t_{BD} \qquad (15)$$

In our case: t_{START} = 0.5 ms. This time represents how long the electrons are being accelerated. To find the first peak we must set parameters like: minimum peak height and threshold to eliminate the noise.

I_{HXR} (size of single peaks)

To find single peaks we will zoom the graph shown in previous figure and estimate their size (Figure 11). As we have said before, individual spikes are HXR photons resulting from the impact of high energy on the limiter. We are calculating the energy of a single photon, thanks to calibration with isotope Cs.

Single peaks

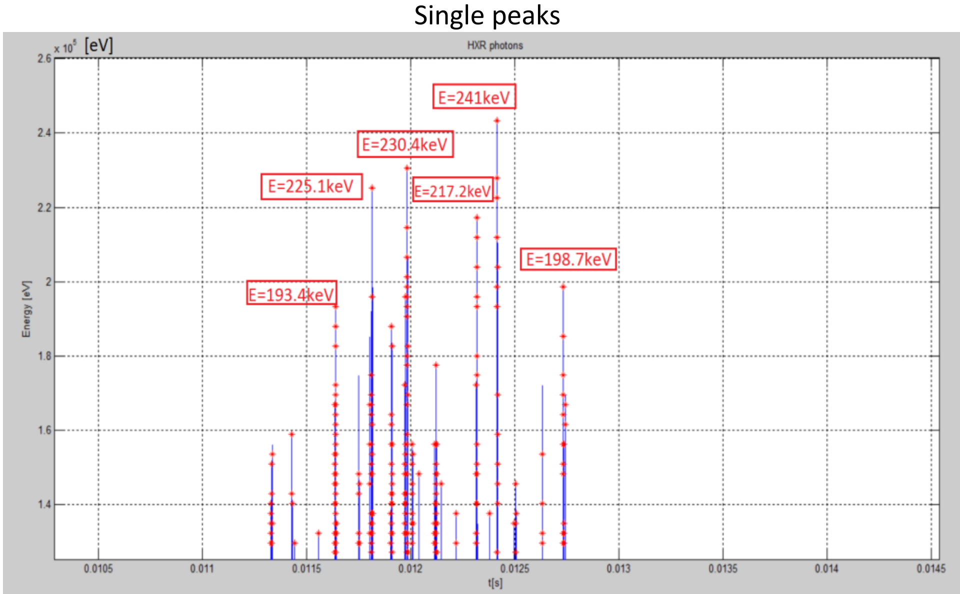

Figure 11.

N (number of peaks)

We will use the procedure shown before. It is important to say that we can't calculate the exact number of the all peaks, but we can calculate approximate number with high precision (Figure12).

Assumption of all peaks

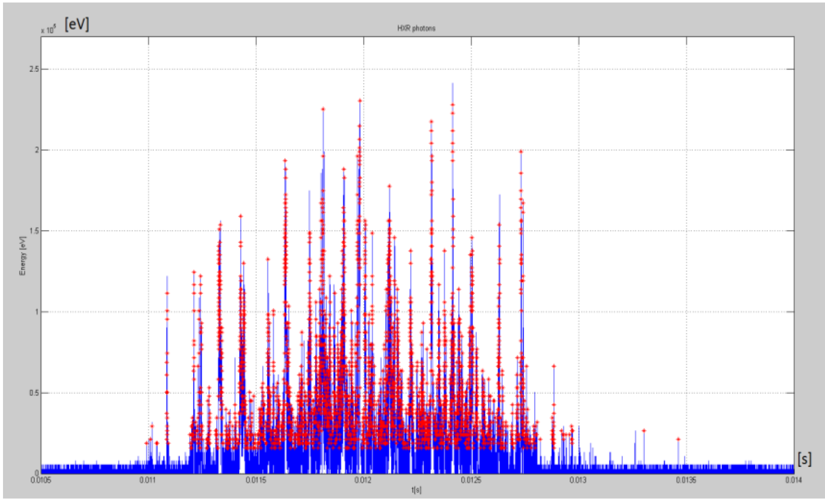

Figure 12.

In this case N=3828.

S (integrated HXR signal over the whole discharge)

As we have said S represents whole energy of runaway electrons that is detected. In this case S = 219.80 MeVs. The units for S is eV*s because we integrate during the time. This parameter is not very reliable, because the width of peak depends only on the electronics. If you would change the impedance of data acquisition, the value of S would be changed.

4) Estimation of critical velocity, critical electric field and Dreicer field.

To estimate these parameters we have to estimate first value of E, n_e and T. We have used graphs from Figure 8 to find the average value between the breakdown and the plasma end, which is shown in Figure 13.

Graphs with calculated average value during plasma life

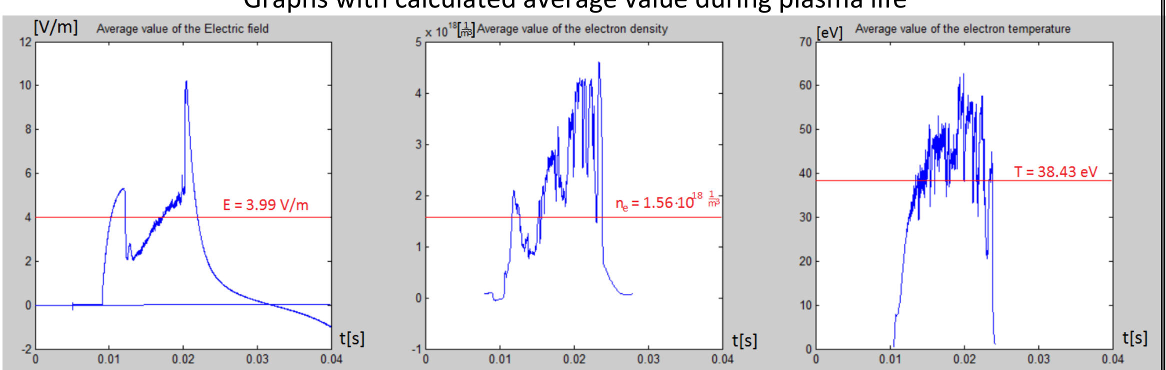

Figure 13.

Now we should only put these average values in formulas 1, 2, 3 to find critical velocity, critical electric field and Dreicer field.

$v_c \approx 5.18 \cdot 10^6$ m/s	$E_c \approx 0.0012$ V/m	$E_D \approx 15.89$ V/m

DISCUSSION OF RESULTS AND CONCLUSION

1) Estimated energy is higher than the energy measured by scintillator detector. In theory, electron should be accelerated afterwards the breakdown until the detection of the first peak in HXR signal (Figure 14). It can be seen that theoretically estimated energy in the moment of the first peak has value of 758 keV. The reason for this is:

- RE->HXR conversion can occur in multiple stages and all energy is not converted to HXR radiation
- Even if all energy would be converted to HXR radiation, it will not always be captured by the scintillator crystal (it can be just slow down, and pass through as a photon of lower energy)
- We have assumed that the electron is accelerated in a vacuum, thus there was no drag force that would slow down the acceleration, but it is there in the reality

Graph of estimated energy of an electron and HXR signal

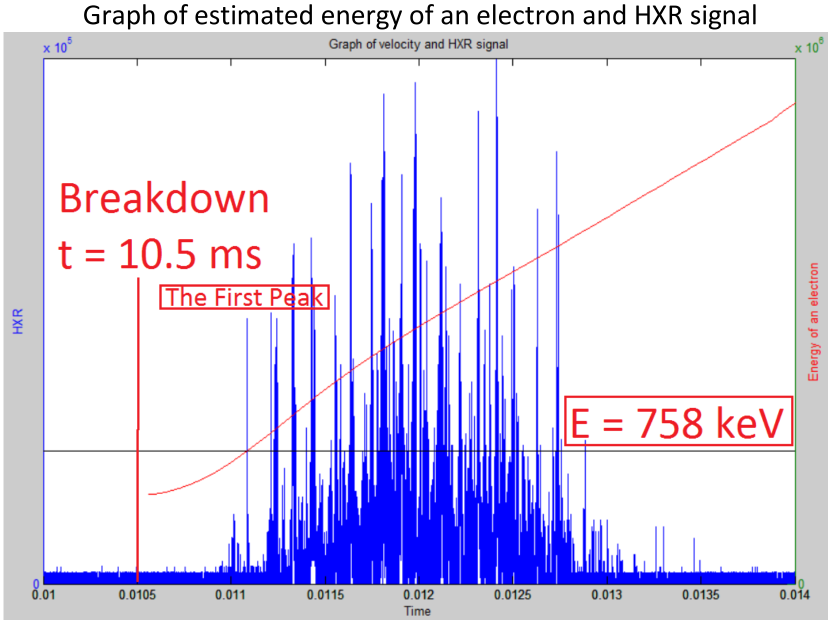

Figure 14.

The ratio between the theoretical energy with the highest peak is about 3 what is expected.

2) The second conclusion is that the moment after reaching the critical velocity, electrons radiate in HXR-spectrum and become detected (Figure 15). It is important to say that the electrons are lost soon after they would reach the critical velocity in the vacuum model. Also duration of detecting HXR signals is about 2.5ms, which is more than five time less than plasma lifetime. With red line is denoted theoretically calculated velocity from Figure 4 and green line represents calculated critical velocity.

Graph of velocity and HXR signal

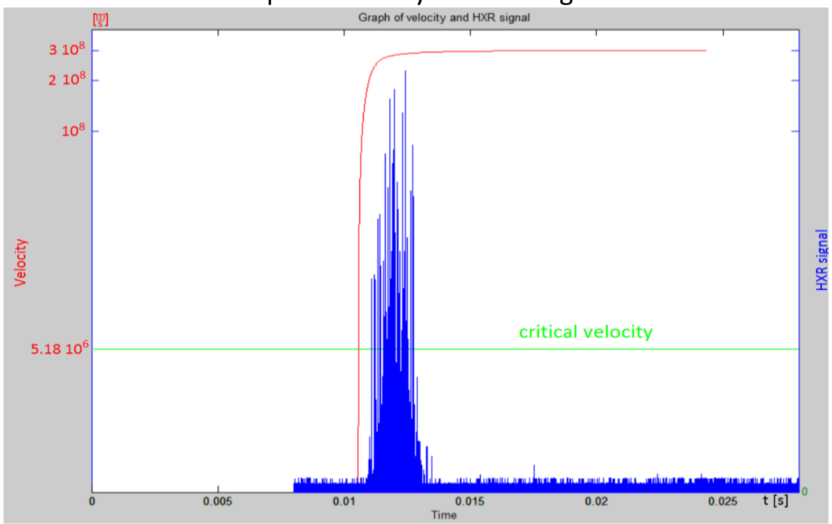

Figure 15.

3) The number of the runaway electrons increase with increasing the electron density (Figure 16). It is not expected in compare with the older thesis “Runaway electrons in the tokamak and their detection”, written by Lenka Kocmanová (Figure 17). The pressure of the working gas (H_2 in this case) from Figure 17 should behave similar like the electron density, therefore it is expected decreasing trend in Figure 16. Reasons for the obtained results could be imperfections of detection methods and the equipment. In Figure 16 are used shots number 22445, 22449, 22452, 22477 and 22496.

Dependence of the number of peaks from the electron density

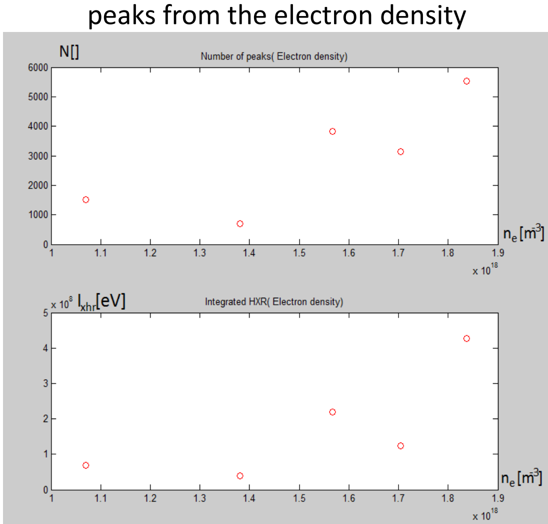

Figure 16.

Expected results

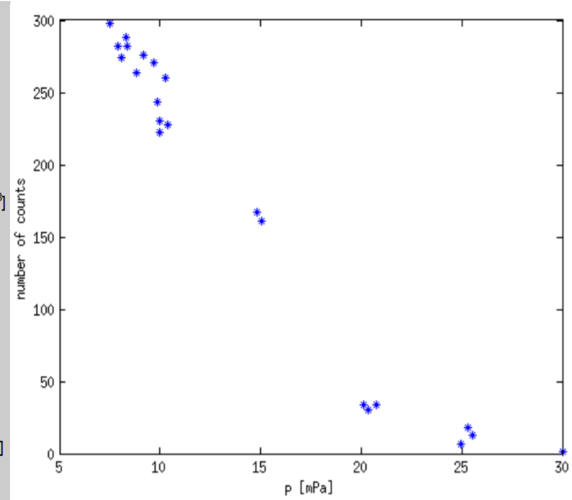

Figure 17.