# Nuclear Fusion Workshop

# EXPERIMENT REPORT

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| **Title** | Investigation of Plasma Fluctuations by Mean of Probes |

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*Fusion Days @NS*

*26-30 Septembar 2016*

*Faculty of Natural Sciences*

*Novi Sad*

**Abstract**

Fusion Education Network is a non-profit organization with the aim of popularizing fusion education in the Western Balkans, and has organized workshops in which several experiments were done. This paper is a report on one of these experiments. It presents a case study of data analysis from measurements done on tokamak GOLEM in Prague. The goal was to investigate the correlation between main plasma parameters and plasma fluctuations, as well as to find the fluctuating poloidal plasma velocities, utilizing Langmuir probes as measurement equipment. The approach described in this paper involved determining floating potentials of plasma, which required several theoretical approximations in order to make the experiment feasible. Assuming the electron velocity distribution as a Maxwellian function, the temperature inside plasma bulk as a constant and the Langmuir probe as a planar probe has, as a consequence, allowed the formulation of equations that bonded floating potentials with poloidal velocities and plasma fluctuations. The experiment was successfully executed, quantitative values for poloidal velocities and optimal conditions for the least amount of plasma fluctuations have been found. Taking into account that many estimations and assumptions were necessary in calculations, these results should be carefully used.

**Keywords**: tokamak GOLEM, Langmuir probe, floating potential, plasma fluctuations, poloidal velocity

# 1 Introduction

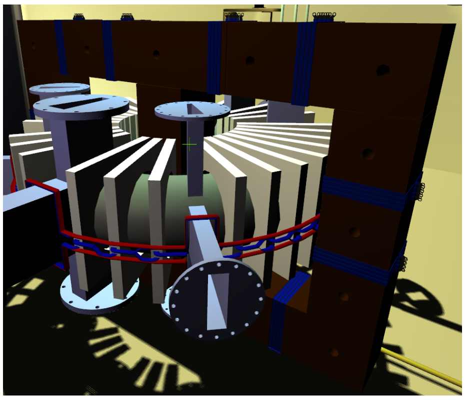
In fusion physics it is essential to understand how the behavior of plasma depends on certain parameters. In order to gain energy from fusion, plasma must be heated to a temperature of around 100 million degrees Celsius. There are no materials capable of withstanding such a high temperature, so plasma must be isolated from the surroundings in a vacuum chamber and contained in strong magnetic fields.

Even though plasma is considered to be contained, on the microscopic scale there are always particles hitting the chamber with tremendous speeds, damaging the chamber and surrounding equipment. A common research goal is to minimize these resulting plasma-chamber interactions or in other words to maximize plasma stability.

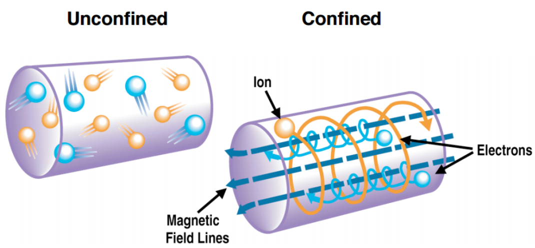
This experiment's aim was to calculate the fluctuating poloidal velocity of particles and find the equilibrium when plasma turbulence is lowest. By measuring floating potentials from 12 Langmuir probes uniformly placed on the radial axis in different plasma conditions, it is possible to acquire statistical information on fluctuations of electrical potential inside plasma bulk and interpret it as turbulence, as well as calculate the radial evolution of velocity fluctuations between consecutive probes.

## 1.1 GOLEM and the Langmuir (rake) probe

The experiment was done via internet on a small tokamak in Prague called **GOLEM**. The working gas was hydrogen conventionally pressurized to 20mPa. The tokamak consists of many coils evenly placed around the vacuum vessel that create a **toroidal magnetic field** *(on Fig. 1a they are inside gray plates)*, and a central solenoid *(in the shape of a transformer, colored brown with blue* *coils on Fig. 1a)* that creates a **poloidal magnetic field**. Both of these are used in order to confine plasma and orient heated plasma particles *(see Fig. 1b)* so that there is less turbulence. The toroidal and poloidal magnetic fields are controlled with voltages going across capacitors charging them, and are labeled $U_B$ and $U_{CD}$ respectively. Also, it is possible to control the **time delay** of the central solenoid's activation relative to the activation of the toroidal magnetic field, assigned with $T_{CD}$. Other important parameters can be found in [5] and [6].



(a) Toroidal and poloidal coils in GOLEM




(b) Plasma confinement

Figure 1

**The Langmuir probe** is an instrument used to calculate Volt-Ampere *(I-V)* characteristics of plasma. It can be made in several models. The simplest one would be to create a small, conducting rod in order to decrease interference in plasma fluctuations as much as possible. On the other hand, a spherical Langmuir probe gathers more ionized material and consequently a more representative electric current flows through the probe. Since for this experiment only the floating potential was required *(no current)*, rods winded to voltmeters with very high resistivity *(in the range of* $M\Omega$*)* were used. As a consequence the voltmeter measures only floating potentials. The probe has to withstand extreme temperatures, and for that reason it is most commonly made out of tungsten or molybdenum with a ceramic insulation *(except for the tip of the rod that is in contact with the plasma)*.

In this experiment we have worked with a **rake probe**, which consists of 12 Langmuir probes, arranged consecutively on a stick with a distance of 2.5 millimeters between neighboring probes. They are numbered from 1 to 12, where 1 is deepest in the plasma, at a distance of 67mm from plasma center and 12 is closest to the rim, being located at the 67+12*2.5=$97^{th}$mm. The limiter *(called limiter because it bounds plasma confinement area)* is located at the $85^{th}$mm, so probes numbered from 8 to 12 are outside plasma bulk, in its "shadow". Rake probe is called "rake" because it resembles a rake used to sweep fallen leaves.

## 1.2 I-V characteristics of plasma

The simplest means used in probe theory to analyze Volt-Ampere characteristics are based on assuming that:

1. the probe current corresponds to collection of charged particles drown from a plasma, whose volume is much larger than the probe volume, and formed by neutral atoms, positively ionized atoms, and electrons *(see [4])*.

2. the velocities of these particles follow a Maxwellian distribution *(see eq. 1)*, where $k_B$ is the Boltzmann constant, $T_e$ electron temperature and $V_s$ space *(plasma)* potential.

$$f(v) \propto exp\{-(\frac{mv^2}{2} + \frac{V_{probe} - V_s}{k_B T_e})\} = exp\{-\frac{e|V_{probe} - V_s|}{k_B T_e}\}exp\{\frac{-mv^2}{2k_B T_e}\} \quad (1)$$

In these conditions, probe biasing potential $V_{probe}$, probe geometry and plasma parameters are the only things that affect the I-V curvature. On a typical I-V curve *(see Fig. 2)* we can notice three distinct areas:

- **the electron saturation region**, where $V_{probe} > V_s$. Most of the electrons going towards the probe are collected whereas ions are rejected. The electron current can be calculated as:

$$I_{es} = \frac{eSn_e < v_e >}{4} = eSn_e\sqrt{\frac{k_B T_e}{2\pi m}} \quad (2)$$

  where S is the area of the tip of the Langmuir probe and $n_e$ is electron density, and $< v_e >$ average electron speed.

- **the transition region**, where $V_{probe} \leq V_s$. Electrons are being partially rejected. If electrons are considered Maxwellian, then this part of the curve is exponential *(see eq. 3)*, and we can calculate the plasma electron temperature and electron energy distribution function.

$$I_e = I_{es}exp\{e\frac{V_{probe} - V_s}{k_B T_e}\} \quad (3)$$

  It is very difficult to get dynamic temperature data, so in this experiment we will consider $T_e$ to be a constant.

- **the ion saturation region**, where the probe potential $V_{probe}$ is a lot more negative than the space *(plasma)* potential $V_s$ *($V_{probe} << V_s$ while $|V_{probe}| >> |V_s|$)*. Most of the ions going towards the probe are collected whereas electrons are rejected. There are several theories from which the ion saturation current can be calculated, but they will not be described here *(see [1])*.

Conventionally, the electron current $I_e$ is considered to be positive and the ion current $I_i$ is considered to be negative, so the actual measured current, called plasma current, is equal to $I(V_p) = |I_e(V_p)| - |I_i(V_p)|$. It needs to be stated that $I_i$ and $I_e$ are theoretically derived and cannot be measured separately when their values are similar *(i.e. in the transition region)*. On the other hand, in the saturation regions where almost all either electrons or ions are repelled, it can be approximated that the plasma current is saturation current $I_{is}$ or $I_{es}$. The ion saturation current intensity is much lower than the electron saturation current because ions have much higher masses, so we can often approximate plasma current measurements in the transition region with electron current measurements *(see eq. 3)*.

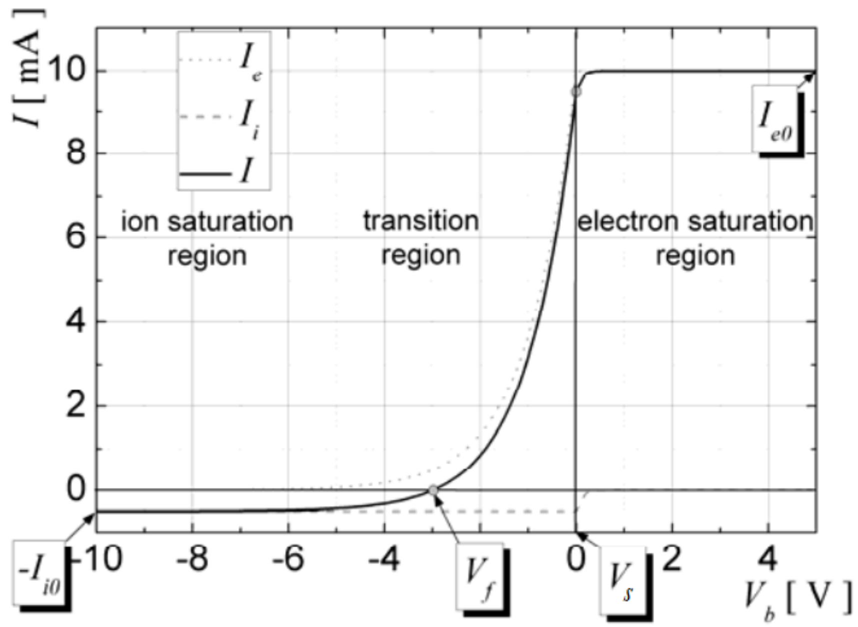



Figure 2: Typical I-V characteristics

### 1.3 Floating potential

The **floating potential** is defined as the voltage when $I_e = I_i$, or in other words in the Langmuir probe there is no current *(see Fig. 2)*. The electron saturation current is given by eq. 2, while the ion saturation current can be calculated using the Bohm criterion *(see [2])*:

$$I_B = \alpha neSv_s, \quad v_s = \sqrt{\frac{k_BT_e}{M}} \tag{4}$$

where M stands for ion mass and $\alpha$ stands for the ratio between the ion density close to the probe and the density in the main plasma, $n_p/n$. The value of $\alpha$ varies but can be approximated as 0.6.

Following postulates 1 and 2 from subsection 1.2 and assimilating equations 3 and 4 into one *(since there is no current flowing through the probe)* we get:

$$V_f = V_s - \frac{k_BT_e}{2e} ln(\frac{2M}{\pi m}). \tag{5}$$

This equation gives us a direct correlation between the floating potential and the plasma potential. When $V_f$ is measured the difference $V_s - V_f$ becomes a little larger because of probe geometry, which can be solved with a geometrical correlation.

Since we did not have the means to calculate temperature fluctuations, we assumed $T_e$ to be constant in the plasma . This assumption creates a correlation between space and probe potentials, making their fluctuations equal:

$$V_f + \tilde{V_f} = V_s + \tilde{V_s} - \frac{k_BT_e}{2e} ln(\frac{2M}{\pi m}) \Rightarrow \tilde{V_f} = \tilde{V_s} \tag{6}$$

### 1.4 Estimating poloidal velocity

From equation 6 we can see that the Langmuir probe, when measuring floating potential fluctuations, is actually measuring the fluctuations of space potential, and the measurements, when plotted, are a y-axis translation of $V_f[t]$. Differences between neighboring probes are radial voltages, from which we can calculate fluctuations of the radial electrical field, and hence, because $\vec{E} \times \vec{B}$ is in the poloidal direction *($\vec{B}$ stands for toroidal magnetic field)*, fluctuations of the poloidal velocity:

$$\tilde{E}_r = -\frac{d\tilde{V}_s}{dr}\vec{u}_r = -\frac{\tilde{V}_{LP1} - \tilde{V}_{LP2}}{L}\vec{u}_r$$

$$\vec{v}_p = \frac{\vec{E} \times \vec{B}}{B^2} \tag{7}$$

where $V_{LP1}$ and $V_{LP2}$ are potentials of two consecutive probes. The magnetic field B is considered constant, and was measured with spiraled coils independently.

### 1.5 Standard deviation and coefficient of variation

In this project we were dealing with large amount of data for floating potential values in real time. Thus it was necessary to find average values, and relative values. Since we were interested in plasma fluctuations, **standard deviation** was used to quantify the amount of turbulence:

$$SD = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}|V_f - \mu|}, \quad \mu = \frac{1}{N}\sum_{i=1}^{N}V_f$$

where $\mu$ represents the mean value. **Coefficient of variation** was used as a measure of dispersion of measurements:

$$CoV = \frac{standard\ deviation}{mean\ value}$$

## 2 Procedure and analysis method

Shots were taken on the tokamak GOLEM in 2015. Already existing data from previous experiments was used *(shots numbered from #19988 to #20019)*, because there were problems in recording data from the rake probe at the beginning of the workshop. Later, when the the problem was solved and data was analyzed, two shots were made *(#22495 and #22496)* in order to compare results with the old ones. There were 3 sets of shots, since three parameters exist ($U_B, T_{CD}, U_{CD}$) and in each set only one parameter was a variable, with a step of 100V in the case of $U_B$ and $U_{CD}$, and 1.0ms in the case of $T_{CD}$.

Analysis was done in a multi-paradigm numerical computing environment called MATLAB. Only good quality shots were analyzed, whose plasma current plots had a characteristic "∩" shape *(if it did not look to the naked eye like a "∩" shape the shot was discarded)*, and all checked pre-shooting conditions were within boundaries. These conditions included $U_B$, $T_{CD}$, $U_{CD}$, gas pressure and discharge gas. From the given set of 32 shots, 24 were labeled as satisfactory.

Data, besides the initial three variables, consisted of time dependent plasma current intensity in GOLEM, and time dependent floating potentials for each of 12 probes *(probes being on different radii from container edges have unequal turbulence and micro-environments)*. Plasma current $I_p$, as well as $\vec{B}$, was measured with coils. Plasma current data was used because it was assumed that at it's peak, the gradient of the $I_p$[t] curve is low and is more or less constant, so plasma is more stable around the peak than in the ramped up and down parts of the plot *(we were searching for most stable plasma)*.

**Firstly**, noise was cropped out from the data. Since plasma current is time dependent, and it's plot has a " $\cap$ " shape, an intermediary time interval was defined, outside of which all data was considered noise. Because the process was automatized for all plasma current files *(one file per shot)*, it was checked every time for mistakes within the cropped out data, but there were not any. For example, on Fig. 3 there are two vertical lines at the beginning of the plots, which are obviously noise and were successfully cropped out.

**Secondly**, the maximal plasma current value and corresponding time was found for each of the shots. Afterwards, a small time interval around the maximum was taken *(see Fig. 3)*, for which the current intensity would not decrease by much. These intensities had an approximately equal value at the edges of the time interval. Sometimes there were several peaks with the same value, so the first one *(with smallest time value)* was used as the referential peak.

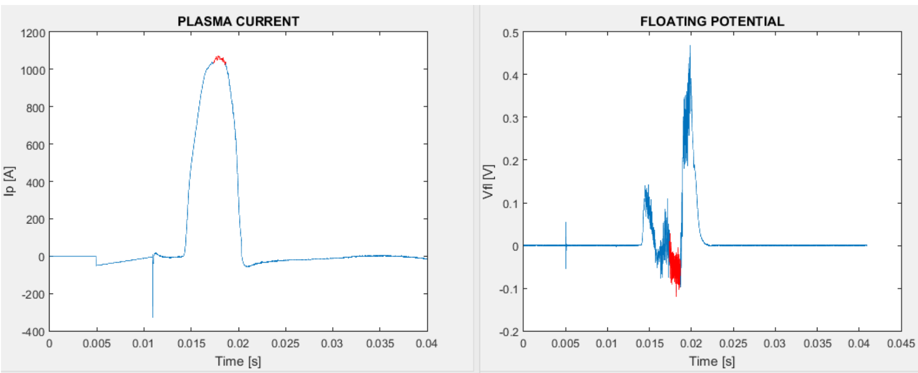



Figure 3: Plasma current and floating potential plots

**Thirdly**, the floating potential data was plotted for the previously mentioned time interval, in order to manually check the interval's plausibility. In case the plotted curve deviates to much from a straight horizontal line, the interval was reduced or enlarged, depending on the situation. On Fig. 3 the red colored parts of plots represent the interval taken.

**Fourthly**, when the interval was determined, mean values, standard deviations and coefficients of variation were calculated from the floating potential data of probes deepest in the plasma, numbered "1" in each shot. The local minimums of the standard deviation values for all 3 sets of shots were found, in order to determine optimal plasma stability conditions. *It was assumed that plasma is most stable when the found local minimum parameters are combined.*

**Finally**, mean values and standard deviations from all Langmuir probes of shots numbered #20004, #20007 and #20013 were calculated and later used to find the poloidal electrical fields and velocities. *Because of the extensive amount of work, and limited amount of time at the workshop, poloidal velocities from only 3 randomly chosen shots have been calculated.* The approach used could not be automated since every plot had to be inspected and time interval corrected by hand. In the end, the relationship between poloidal field fluctuations and mean magnetic field values was discussed, with reference to the results of shots #20004, #20007 and #20013 *(Fig. 4)*.

# 3 Results

In figure 5, six plots are shown: standard deviations and coefficients of variance for $U_B$, $T_{CD}$, and $U_{CD}$ variation sets respectively. Constant parameters for $U_B$ were t=6.0ms and $U_{CD}$=400V; for $T_{CD}$ were $U_B$=600V and $U_{CD}$=400V; and for $U_{CD}$ were $U_B$=600V and $T_{CD}$=6.0ms. In these plots we can see that in the case of $U_B$ and $T_{CD}$ sets SD and CoV are on average lower for smaller x-axis values. This fits the expectation, since lower parameters induce a lower-intensity plasma current. Unfortunately, nothing can be said about the $U_{CD}$ set, because we have no data for voltages lower than 400V. CoV plots show that the mean values of plasma potential have very large error margins, from around 0.5 up to 6 times the mean value. In case of the shot with parameters ($U_B$=600V; $T_{CD}$=6.0ms; $U_{CD}$=400V), which was repeated at least six times, the standard deviations and coefficients of variation differ a lot for each plot. No two shots are exactly the same, and values can change a lot even for small condition modifications.

This analysis has shown that plasma is most stable with parameters ($U_B$=500; $T_{CD}$=6.0ms; $U_{CD}$=400V), with standard deviation equal to 0.0165V and mean value 0.0508V. Also, parameters ($U_B$=800; $T_{CD}$=6.0ms; $U_{CD}$=600V) induced the lowest mean value equal to 0.0071V with standard deviation 0.0634V. Our own shots with the same parameters, numbered #22495 and #22496 gave totally different results - ($U_B$=500; $T_{CD}$=6.0ms; $U_{CD}$=400V) induced standard deviation 0.0847V with mean potential 0.1022V, and ($U_B$=800; $T_{CD}$=6.0ms; $U_{CD}$=600V) induced mean potential 0.1325V with a standard deviation of 0.0847V. Considering that our results differed a lot from the analyzed given data, it needs to be pointed out that these shots were done in a one year difference, and that plasma conditions at GOLEM have likely changed.

On figure 4 are shown calculated poloidal velocities of shots #20004 *(blue line)*, #20007 *(green line)*, and #20013 *(red line)*. Probes from 8 to 12 are behind the limiter, so they are in the shadow, whereas probes 1-7 are in plasma bulk, which explains the fact that after Langmuir probe 7, there is a sudden drop in velocity. It can be seen that for the lowest mean toroidal magnetic field *(green line)*, poloidal velocities are highest deep in plasma bulk, but decrease fast. Vice versa, the strongest mean toroidal magnetic field has the highest poloidal velocity values close to the limiter. Still, many more shots would need to be made in order to have a conclusive answer.

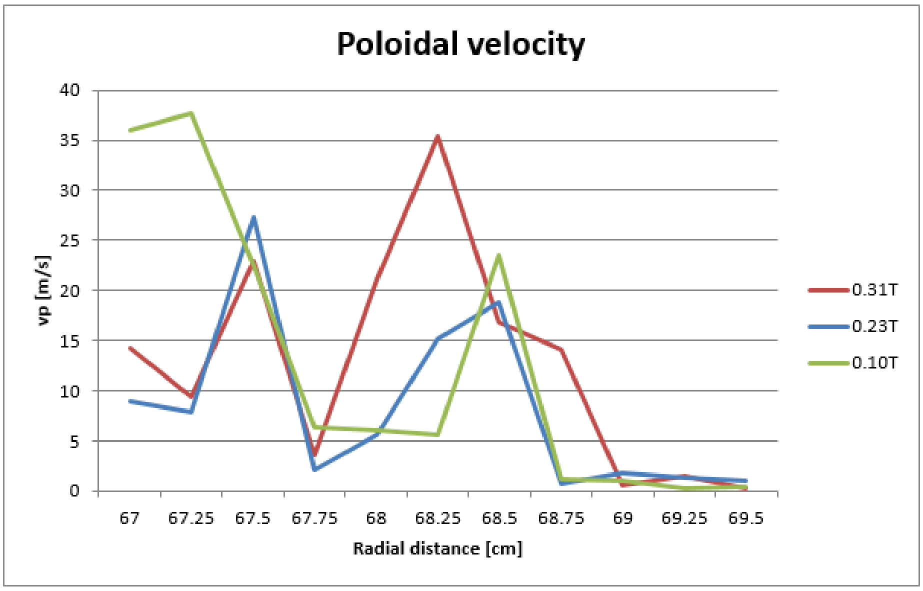



Figure 4

# 4 Discussion

In this experiment, we found what the optimal parameters for plasma confinement are. Also, we calculated the radial evolution of poloidal velocity and analyzed its behavior depending on toroidal magnetic field strength.

Unfortunately, these findings are not conclusive. We made many assumptions during development of this theory. Plasma temperature was approximated as constant, as there were no means to measure it. Different machine conditions caused very different results for the same parameters. Even for two consecutive shots many measurements had different results. We had also assumed that when plasma current is at its peak the observed plasma is most stable. Analysis of collected data, including the interval ranges around the peak of the plasma current plot, was done by hand. It would be really hard to get exactly the same results again with the approach described, unless the used interval is specified beforehand.

The data used was incomplete as there were shots missing for $U_B$ and $U_{CD}$ variation sets. Overall the total number of shots was not enough to make any objective conclusions. It is not possible to guarantee that the minimums found in this experiment for mean and standard deviation potential values are in fact general minimums, until all possibilities have been tested. Last but not least, chosen parameters for shots should be used with a reserve. Even though the requested gas pressure was 20mPa, actual measured pressures varied from 10 up to 30mPa. It would be better to repeat shots until the measured pressure can be approximated to 20mPa. All of this indicates that data was being gathered and analyzed with an error that cannot be described as negligible.

Collected data can be better analyzed if a highpass filter is used to distinguish fluctuations from unwanted information, i. e. noise. Highpass means that the Fourier transformation would filter out floating potential signals below 200Hz

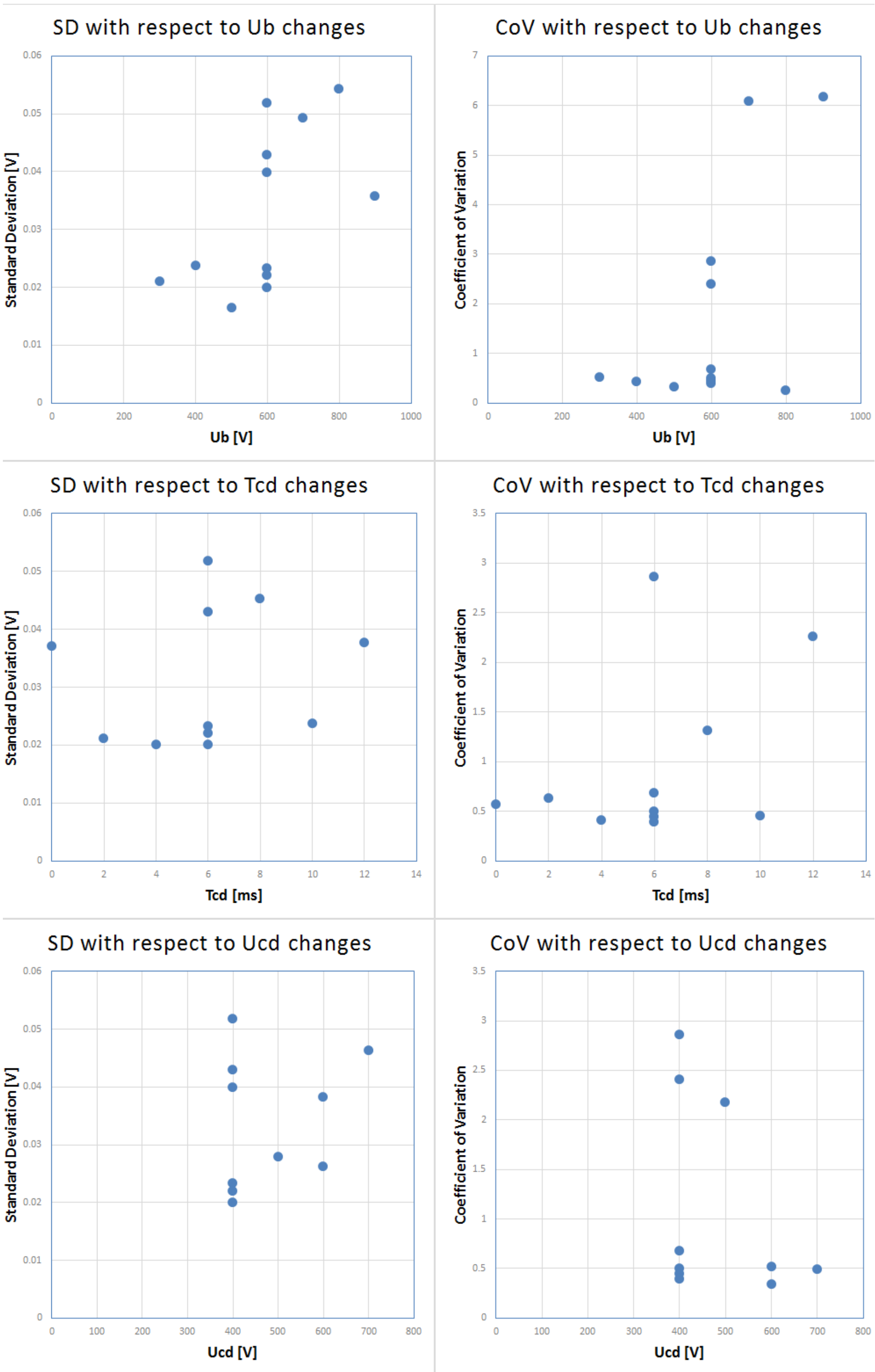



Figure 5: SD and CoV plots for $U_B$, time, and $U_{CD}$ variation sets

by putting their coefficients to zero. Afterwards, by doing an inverse Fourier transformation on the refined data, one would get the required signal. With the new signal, only floating potential fluctuations are acquired *(not the mean part)*, and data of interest is not lost during the cropping process when plasma current is at its peak. The statistical analysis would be done in a much more proficient manner. Standard deviations would probably differ a lot as the new signal plot oscillates around the x-axis with no mean value and no trend, i. e. no low frequency oscillations.

To sum up, with the analysis used, the assumptions that were made (especially electron temperature being constant) were shown to be too weak to provide conclusive information. However, it was very informative and educational for me as a student. The aim, which was to show what it's like to be a scientist and interest students in fusion was in my opinion quite a success.

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