Triple Langmuir Probe

A Langmuir probe triple provides an advantage over single and double probes, allowing simultaneous measurement of plasma parameters without the need to sweep a voltage (bias), which are a limiting factor in the environment of pulsed plasma. [1], [2]

This technique proves to be a powerful tool not only for stationary plasmas but also rapidly changing in time, such as glare recurring or non-recurring, low frequencies of oscillation of plasma, plasma shock waves, etc. It is also useful in circumstances where the device (probe) must be counted quickly move through the plasma, as in geophysics or astronomy applications where spacecraft rocket or carriers are used as probes, or measurement of plasma arcs where the probe can not be maintained within the plasma. [3]

There are two ways to connect electrically triple Langmuir probe, the "Voltage Mode" and "Current Mode", see Figure 1. In the traditional method of operation, referred to "Voltage Mode" (see Figure 1 (a)), the probe (P_3) is brought to float in the plasma, i.e. I_3 (t) = 0, while an external voltage is fixed $V_{12} = V_1 - V_2$ between the probes P_1 and P_2. Measuring the resulting voltage difference V_{13} (t) and the current I_2 (t) = I_1 (t) is possible to obtain the electron temperature T_e (t) and the electron density n_e (t). [1], [4], [5], [6], [7]

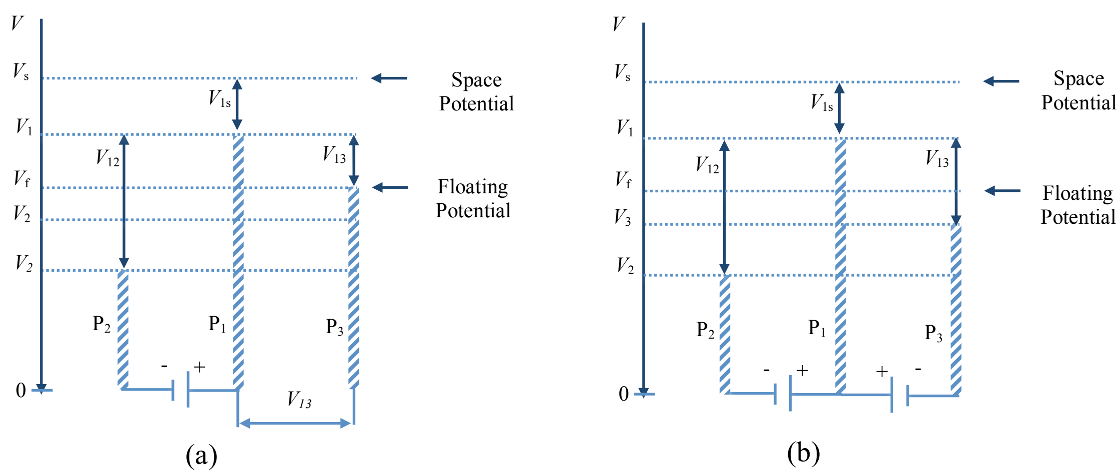


Figure 1. Electrical diagram of a triple Langmuir probes. (a) "Voltage mode". (b) "Current mode".

The other way to work with the triple probe is in the "Current Mode", see Figure 1(b). The motivation to work in this way arises from the fact that the measurement of voltage V_{13} (t) that is floating in the "Voltage Mode" is a high-impedance measurement, which can be susceptible to electromagnetic noise of a pulsed plasma, introducing considerable error in the results. [4]

Current Mode

Applying current models for electrons and ions collected, together with the assumption of $A_1 = A_2 = A_3 = A_{||}$, where A_i is the area of the probe *i*, and $A_{||}$ is the area parallel to flux of plasma. Then it is obtained simultaneous equations

$$I_1 = A_{||} J_{eo} \exp\left[\frac{-eV_{s1}}{kT_e}\right] - A_{||} e n_e \sqrt{\frac{kT_e}{m_i}} \exp\left(\frac{-1}{2}\right) \tag{1a}$$

$$I_2 = A_{||} J_{eo} \exp\left[\frac{-e\left(V_{s1} + V_{12}\right)}{kT_e}\right] - A_{||} e n_e \sqrt{\frac{kT_e}{m_i}} \exp\left(\frac{-1}{2}\right) \tag{1b}$$

$$I_3 = A_{||} J_{eo} \exp\left[\frac{-e\left(V_{s1} + V_{13}\right)}{kT_e}\right] - A_{||} e n_e \sqrt{\frac{kT_e}{m_i}} \exp\left(\frac{-1}{2}\right) \tag{1c}$$

The equation system (1) is used for the current mode. Solving numerically can get the value of T_e, n_e and V_{s1}. This system of equations is only valid only for probes without collisions.

You can manipulate the system (1) to express another system of equations. Subtracting (1a) - (1b) and (1a) - (1c), then divide these subtractions: [(1a) - (1b)] / [(1a) - (1c)], one obtains the equation (2).

$$\frac{I_1 - I_3}{I_1 - I_2} = \frac{1 - \exp\left[\frac{-eV_{13}}{kT_e}\right]}{1 - \exp\left[\frac{-eV_{12}}{kT_e}\right]} \tag{2}$$

Now, solving for the exponential term of (1a), we obtain (3).

$$\exp\left[\frac{-eV_{s1}}{kT_e}\right] = \frac{I_1 + A_{||} e n_e \sqrt{\frac{kT_e}{m_i}} \exp\left(\frac{-1}{2}\right)}{A_{||} J_{eo}} \tag{3}$$

It is replaced (3) in (1b), then it can solve for n_e, equation (4).

$$n_e = \frac{1}{e A_{||} \sqrt{\frac{kT_e}{m_i}} \exp\left(\frac{-1}{2}\right)} \left[\frac{I_2 - I_1 \exp\left[\frac{-eV_{13}}{kT_e}\right]}{\exp\left[\frac{-eV_{13}}{kT_e}\right] - 1}\right] \tag{4}$$

Thus, numerically solving (3) we can obtain the electron temperature T_e, after finding T_e can be found electron density n_e with equation (4) and finally V_{s1} can find the equation (3).

Voltage Mode

In this mode (Figure 1a), since the probe 3 is floating so $I_3 = 0$, and $I_1 = I_2$. Given these conditions, we can rewrite the equations (2) and (4) for T_e and n_e, to obtain the new equations (5) and (6).

$$\frac{1}{2} = \frac{1 - exp\left[\frac{-eV_{13}}{kT_e}\right]}{1 - exp\left[\frac{-eV_{12}}{kT_e}\right]} \tag{5}$$

$$n_e = \frac{1}{eA_{//}\sqrt{\frac{kT_e}{m_i}}\, exp\left(\frac{-1}{2}\right)}\left[\frac{I_1}{exp\left[\frac{eV_{13}}{kT_e}\right] - 1}\right] \tag{6}$$

Experimental Set-up

In order to study the evolution of the temperature in the tokamak GOLEM, we used a Langmuir probe triple mode voltage. The rake probe was placed 66mm from the center of the tokamak chamber, with UB = 600 V, UCD = 450 V, PH2 = 16 MPa, preionización = ON, TCD = 1000 micros. It took two orientations for the probe, the first in DS direction and the second in LFS direction, see Figure 2.

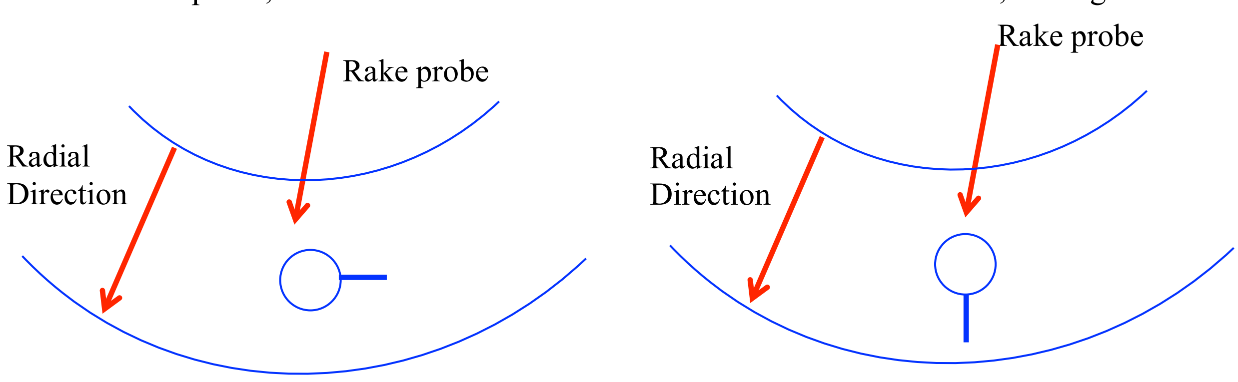


Figure 2. (Left) DS orientation. (Right) LFS orientation.

It was not possible to measure simultaneously I_{sat}, V_1 and V_3. Therefore, they were measured separately. To measure was taken only I_{sat} DS orientation, between probes 1-2 (shot 10192), 2-3 (shot 10193), 3-4 (shot 10194), 4-5 (shot 10195), 5-6 (shot 10196), 6-7 (shot 10197), 7-8 (shot 10198), 7-9 (shot 10199) and 9-11 (shot 10200).

To calculate the temperature was measured at V_1 and V_3 different probes. It is necessary to say that V1 correspond to the probe that is positively polarized and V3 is the probe that is floating, see Figure 1. The measurement was made between; 1-2-3 (shot 10203), 2-3-4 (shot 10204), 3-4-5 (shot 10212), 4-5-6 (shot 10213), 5-6-7 (shot 10214), 6-7-9 (shot 10215), 7-9-11 (shot 10216), 9-11-13 (shot 10217), 11-13-14 (shot 10218), 13-14-15 (shot 10219), for orientation DS and; 1-2-3 (shot 10220), 2-3-4 (shot 10221), 3-4-5 (shot 10222), 4-5-6 (shot 10223), 5-6-7 (shot 10224), 6-7-9 (shot 10225), 7-9-11 (shot 10226), 9-11-13 (shot 10227), 11-13-14 (shot 10228), 13-14-15 (shot 10229), for orientation LFS. Where the first number corresponds to the probe is floating, the second is the positively biased probe and the third probe that negatively polarized.

The circuit according to the triple probe can be seen in Figure 3. Where polarization is made by batteries in series. [8]

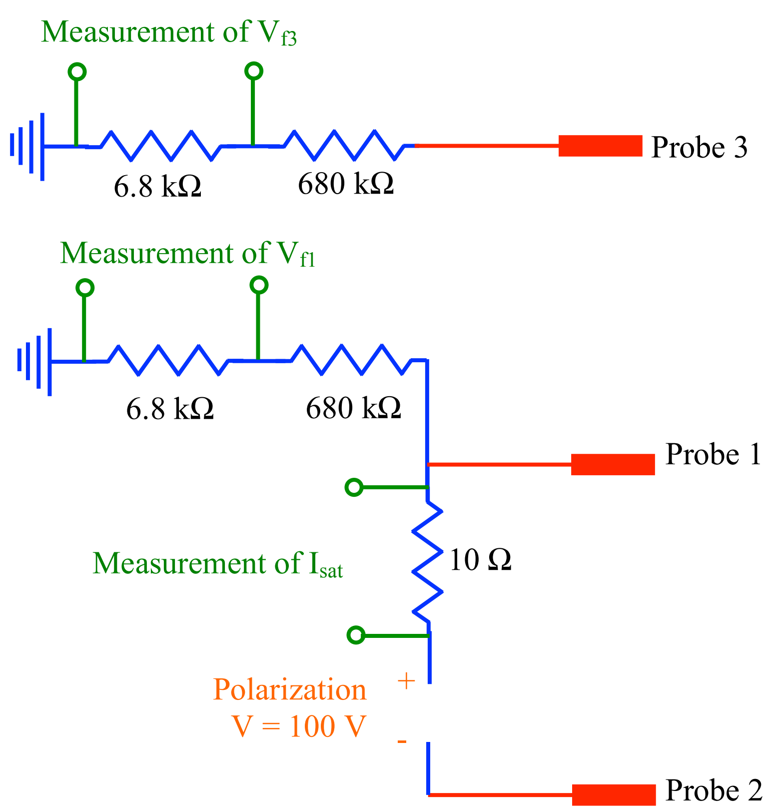


Figure 3. Circuit for triple probe in voltage mode.

Results

To obtain the electron temperature, it was numerically solved the equation (5). Curves were obtained from electron temperature and saturation current. These are plotted individually below. Also plotted surface the temperature (in both orientations, DS and LFS) and Isat.

Averages calculated over time, 7-9 ms, 11.9 ms, 11-13 ms, 13-15 ms, 15-17 ms, 17-19 ms, for Isat and electron temperature in both orientations.

From the graph for the orientation <Te> DS, it is seen that the maximum temperature is 15eV. Temperature decreases for probes that are further away. From the graph for the orientation <Te> LFS, it is seen that the maximum temperature is 25eV. The temperature begins to rise up to 10ms and then begins to decrease, taking 15eV value below. From the graph orientation <Isat> for DS, begins to climb to 10ms and then begins to decrease.

References

[1] N. A. Gatsonis, L. T. Byrne, J. C. Zwahlen, E. J. Pencil and H. Kamhawi, "*Current-mode Triple and Quadruple Langmuir Probe Methods With Applications to Flowing Pulsed Plasma*", IEEE Transactions on Plasma Science, Vol. 32, No. 5, pp. 2118-2129, Octuber 2004.

[2] N. A. Gatsonis, J. C. Zwahlen, A. Wheelock, E. J. Pencil, and H. Kamhawi , "*Pulsed plasma thruster plume characterization using a current-mode quadruple Langmuir probe method*", *J. Propulsion Power*, vol. 20, no. 2, pp. 243–254, 2004.

[3] S. Chen and T. Sekiguchi, "*Instantaneous direct-display system of plasma parameters by means of triple probe*", *J. Appl. Phys.*, vol. 36, no. 8, pp. 2363–2375, 1965.

[4] R. F. Eckman, L. Byrne, N. A. Gatsonis, and E. J. Pencil, "*Triple Langmuir probe measurements in the plume of a pulsed plasma thruster*", *J. Propulsion Power*, vol. 17, no. 4, pp. 762–777, July–Aug. 2001.

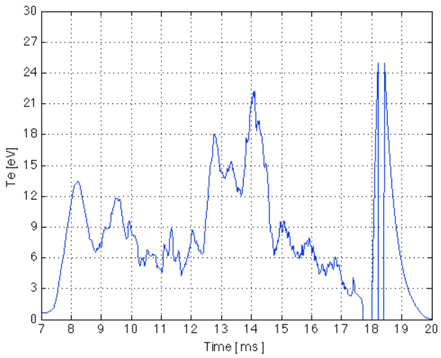
[5] Langmuir, I. and Mott-Smith, H.M., *Gem. Electr. Rev.*, 26: p. 731(1923).

[6] Chen, F.F., *Introduction to plasma physics and controlled fusion*. 2nd ed. 1984, New York: Plenum Press.

[7] Lecture Notes on PRINCIPLES OF PLASMA PROCESSING, Francis F. Chen Electrical Engineering Department, Jane P. Chang Chemical Engineering Department, University of California, Los Angeles, Plenum/Kluwer Publishers, 2002.

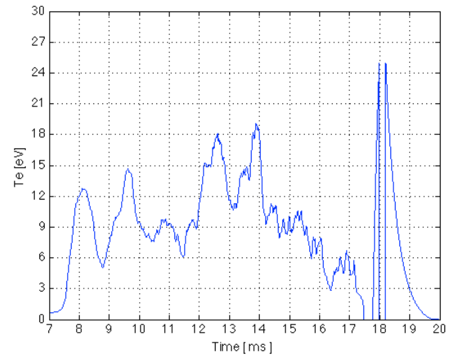
[8] S. G. Lee, "Triple Langmuir probe measurements in the Hanbit magnetic mirror device", Review if Scientufic Instruments, Vol. 72, number 1, pp 442. 2001.

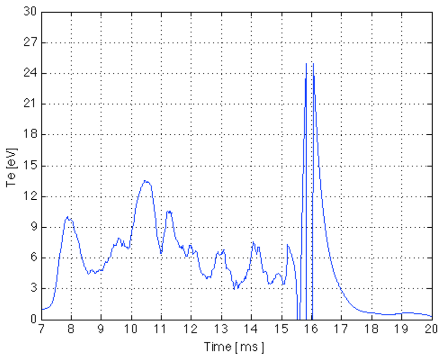
Te in orientation DS



Shot 12203
Probes: 1-2-3

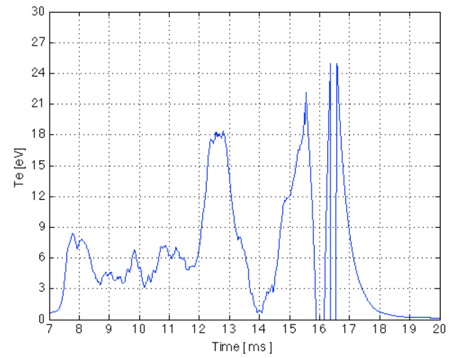
Shot 12204
Probes: 2-3-4

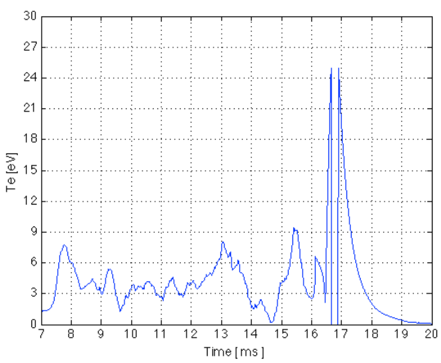




Shot 12212
Probes: 3-4-5

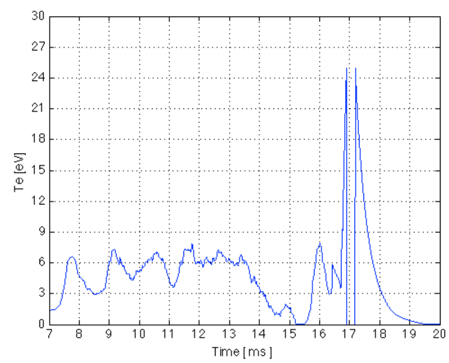
Shot 12213
Probes: 4-5-6

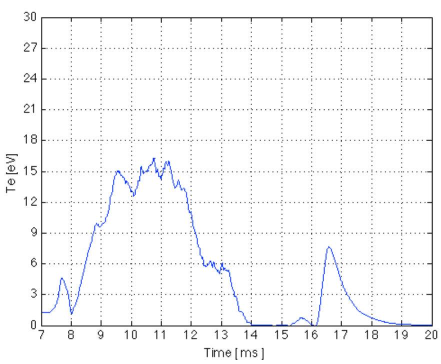




Shot 12214
Probes: 5-6-7

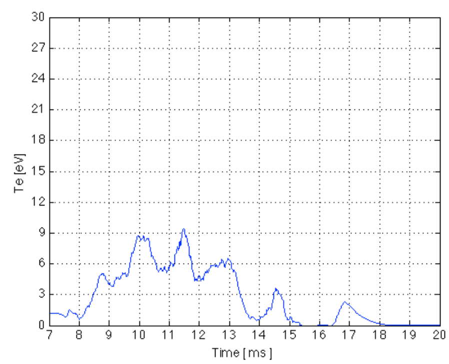
Shot 12215
Probes: 6-7-9

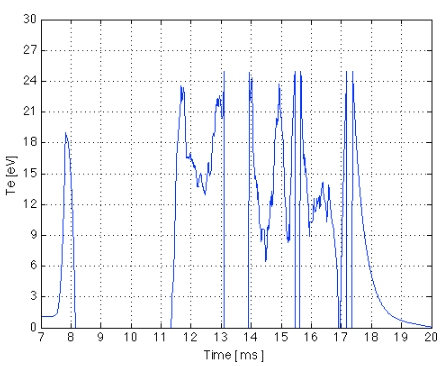




Shot 12216
Probes: 7-9-11

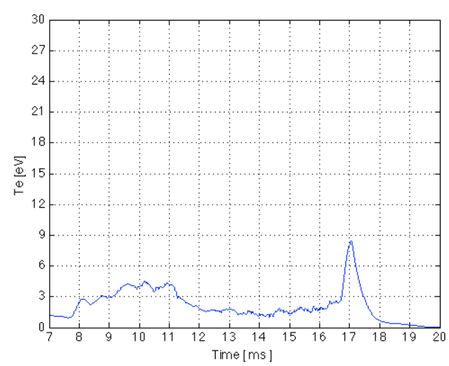
Shot 12217
Probes: 9-11-13





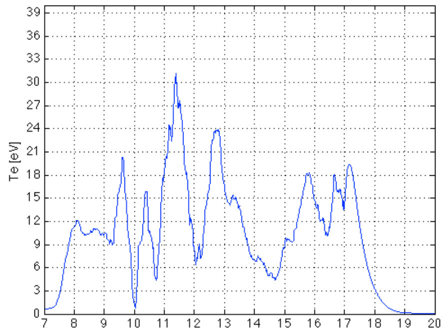
Shot 12218
Probes: 11-13-14

Shot 12219
Probes: 13-14-15

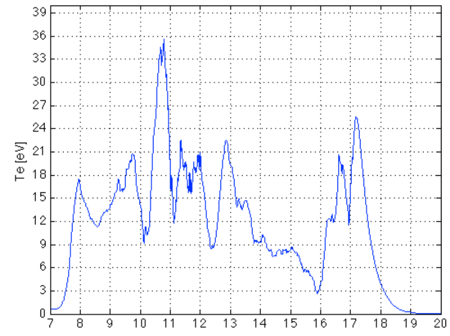


Te in orientation LFS

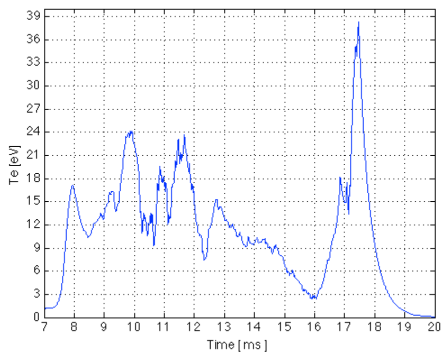
Shot 12220
Probes: 1-2-3



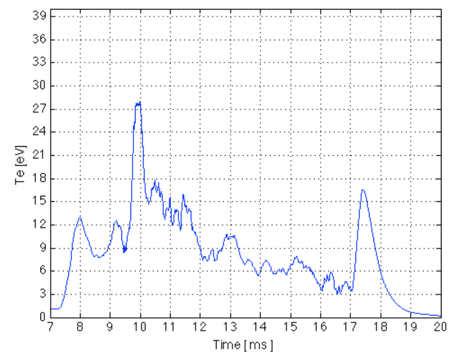
Shot 12221
Probes: 2-3-4



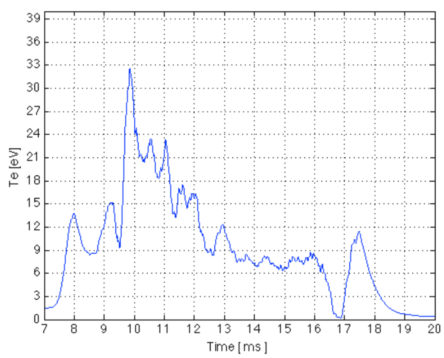
Shot 12222
Probes: 3-4-5



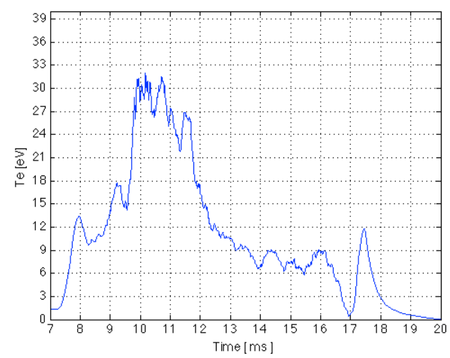
Shot 12223
Probes: 4-5-6



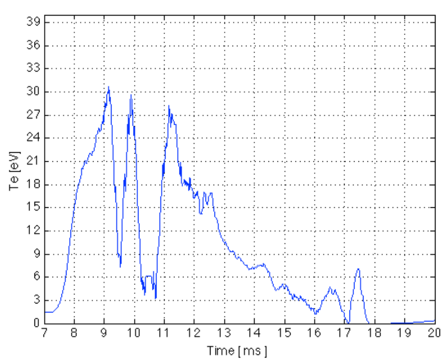
Shot 12224
Probes: 5-6-7



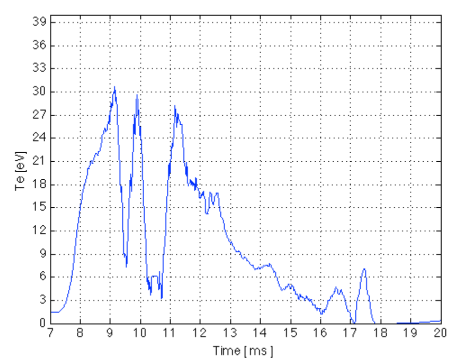
Shot 12225
Probes: 6-7-9



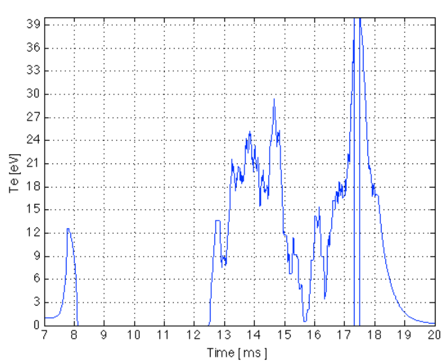
Shot 12226
Probes: 7-9-11



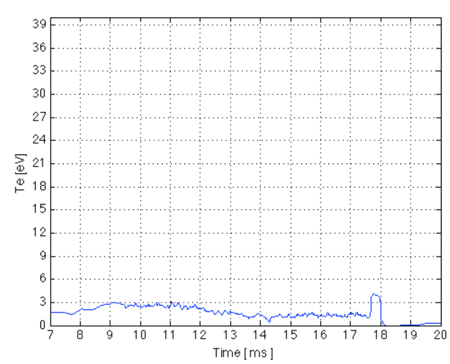
Shot 12227
Probes: 9-11-13



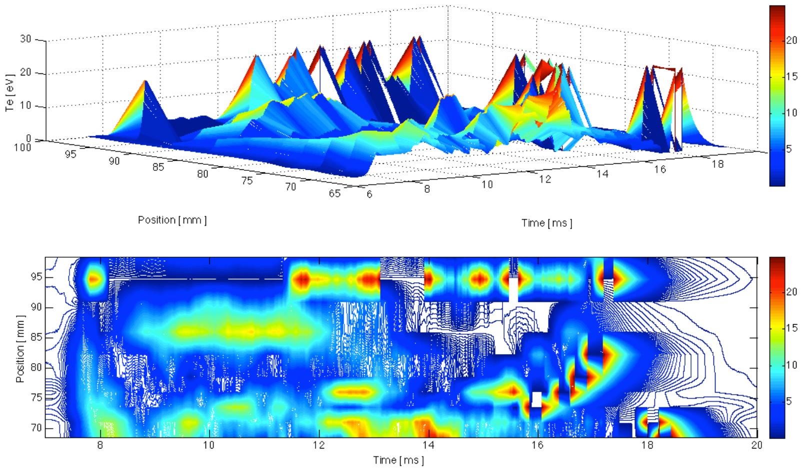
Shot 12228
Probes: 11-13-14



Shot 12229
Probes: 13-14-15



Te in orientation DS



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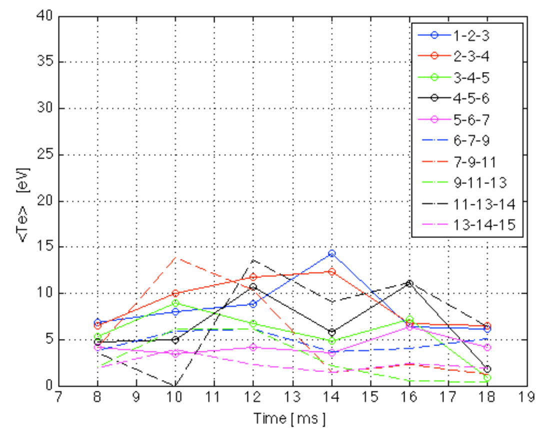
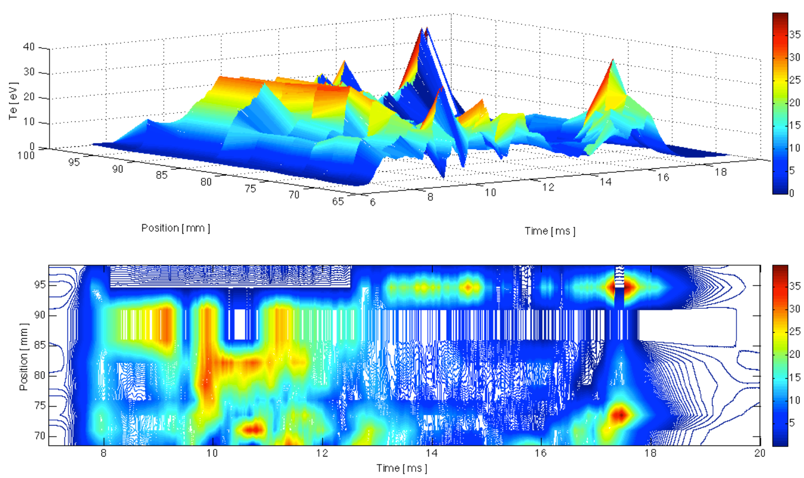
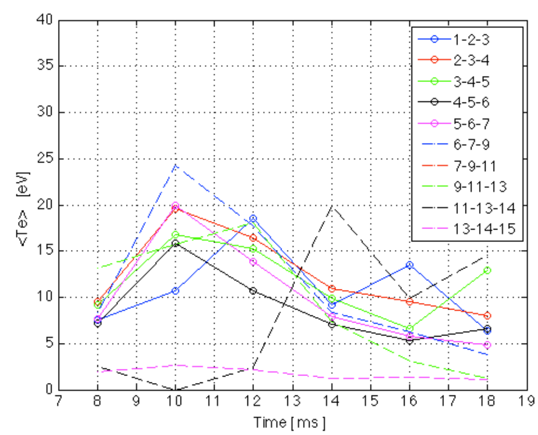


Te in orientation LFS

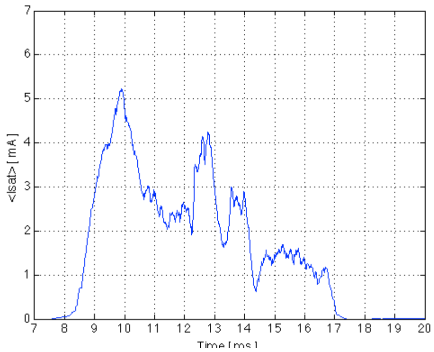


<Te> in orientation LFS

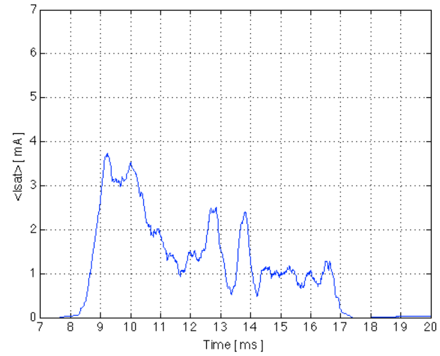


Isat in orientation DS

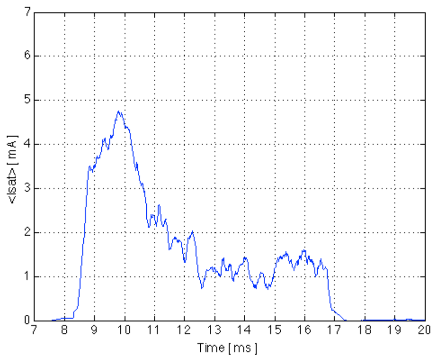
Shot 12192
Probes: 1-2



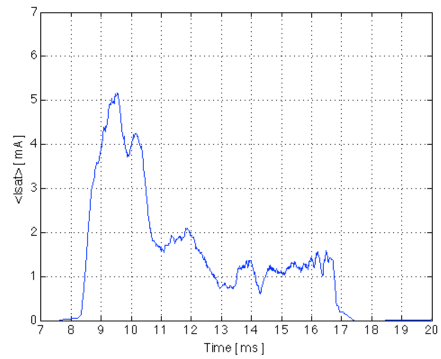
Shot 12193
Probes: 2-3



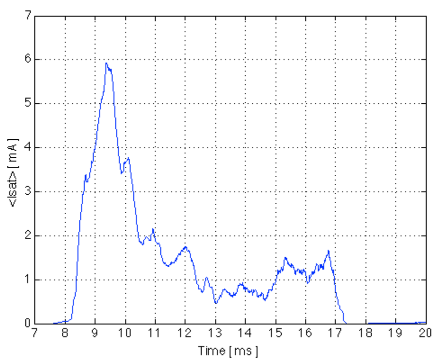
Shot 12194
Probes: 3-4



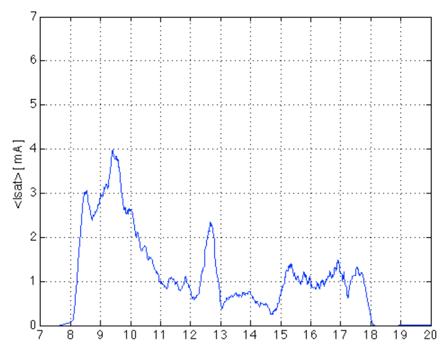
Shot 12195
Probes: 4-5



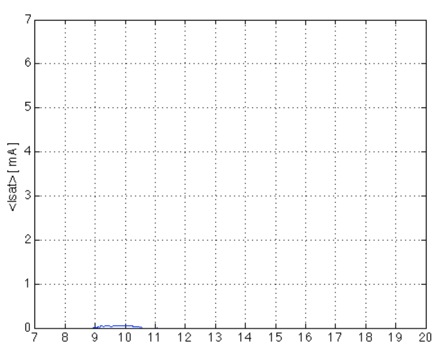
Shot 12196
Probes: 5-6



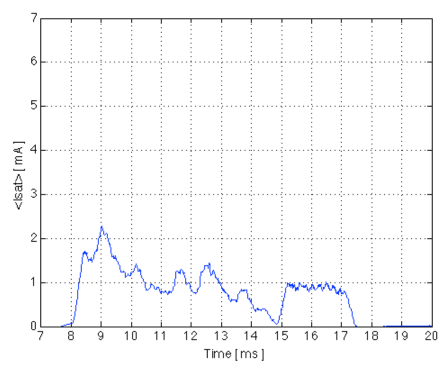
Shot 12197
Probes: 6-7



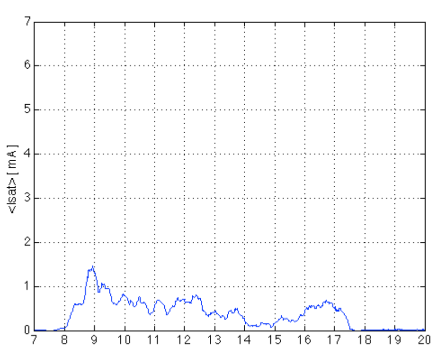
Shot 12198
Probes: 7-8



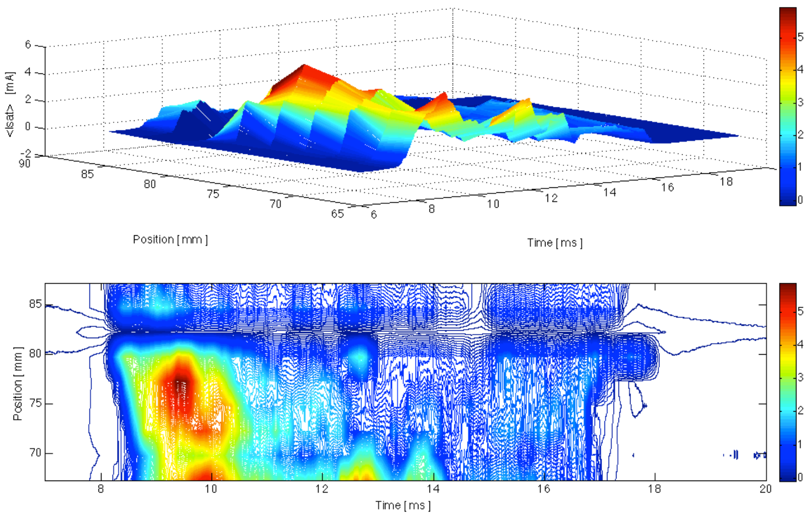
Shot 12199
Probes: 7-9



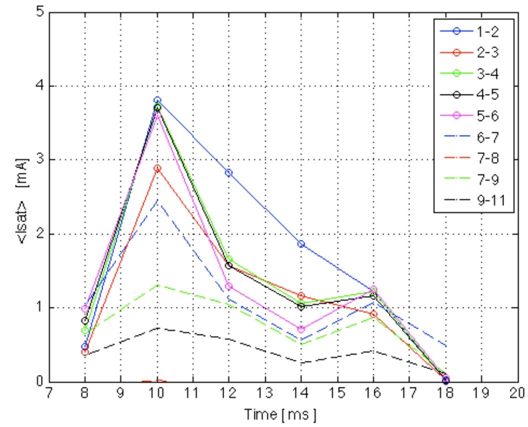
Shot 12200
Probes: 9-11



Isat in orientation DS

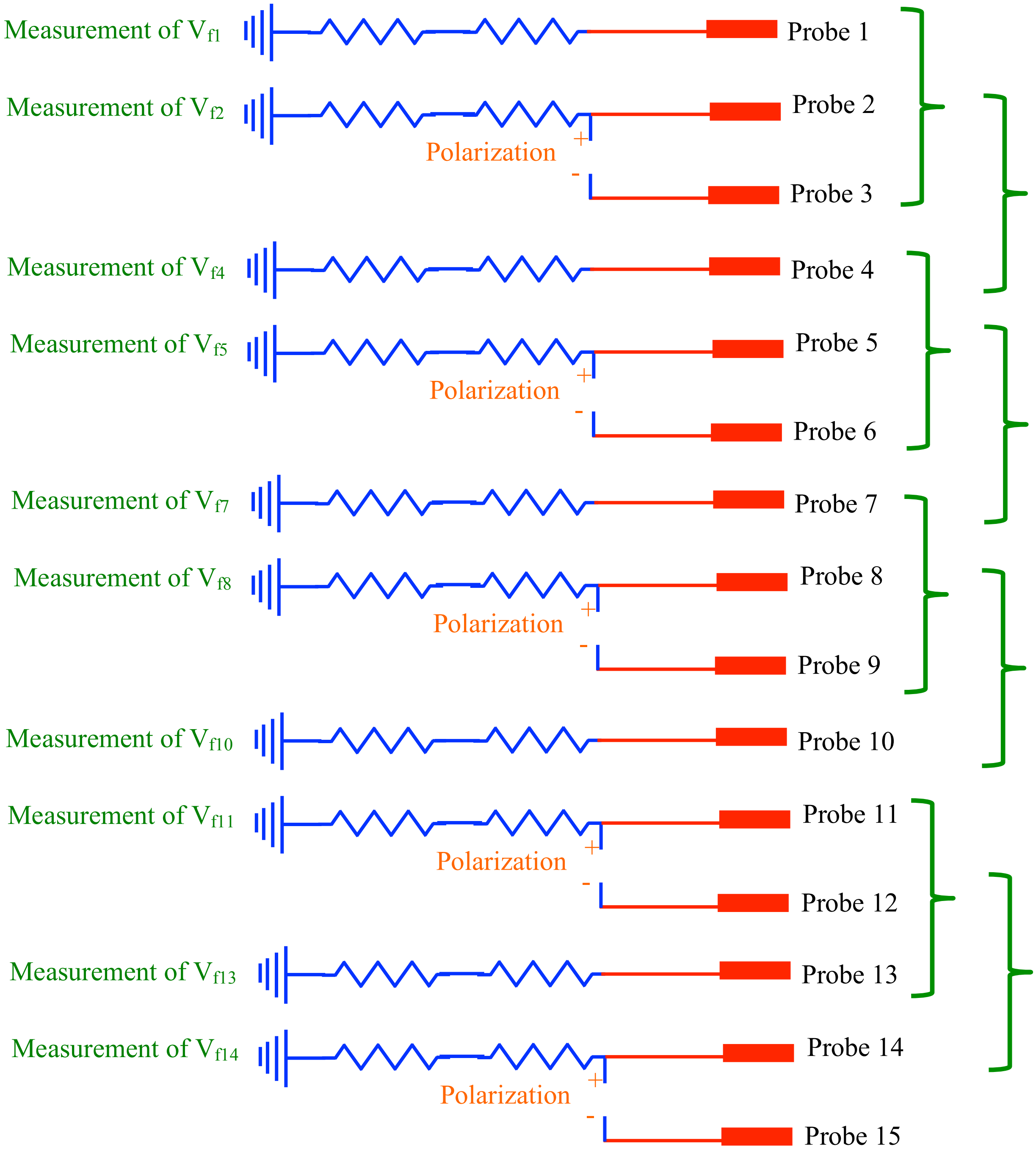


<Isat> in orientation DS



Proposal for Future Work

I propose the following arrangement for probes, probes triple mode. From being merely using probes 15 can have temperature data in 8 different points electrons in the plasma. These averages are marked in the diagram.



Measurement of Vf1
Probe 1
Measurement of Vf2
Probe 2
Polarization
+
-
Probe 3
Measurement of Vf4
Probe 4
Measurement of Vf5
Probe 5
Polarization
+
-
Probe 6
Measurement of Vf7
Probe 7
Measurement of Vf8
Probe 8
Polarization
+
-
Probe 9
Measurement of Vf10
Probe 10
Measurement of Vf11
Probe 11
Polarization
+
-
Probe 12
Measurement of Vf13
Probe 13
Measurement of Vf14
Probe 14
Polarization
+
-
Probe 15