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Single probe diagnostics for the study of plasma parameters in the expander of an open magnetic trap

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Abstract: Method of plasma potential and electrons mean energy measurement by single Langmuir probe in highly fluctuated plasma of magnetic open trap is described. Diagnostics based on this method allows for two types of measurements: plasma potential in the emission probe mode, as well as current-voltage characteristics of the probe, followed by calculating the plasma potential and the average electron energy. All diagnostic elements, including pulse shape recorders, are fully galvanically isolated. Power supply is provided by battery placed on board of the measuring system. Control and synchronization are realized by means of optical communication lines. This diagnostic design allows measurements relate to plasma electrodes, the potential of which fluctuates with a frequency of up to hundreds of kilohertz.

Keywords: Data acquisition concepts; Plasma diagnostics - probes

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2020 JINST 15 P01018

Contents

1 Introduction

Fundamental investigations concerning the problem of controlled thermonuclear fusion are carried out presently in a number of research laboratories using open-type magnetic traps with a linear configuration [1–3]. The growing interest in such systems is caused by the development of powerful sources of neutrons needed to control hybrid fusion-fission reactors with the further development of a fusion reactor for energy production [4]. Key parameter of such system is energy effectiveness that is rapidly increases with electron temperature growth. One of factors that limit electron temperature can be high plasma thermal conductivity along force lines of magnetic field, which is determined by complicated kinetic processes in expanders (regions with expanding magnetic flux beyond magnetic plugs). The main research objectives in this direction are detailed studies of this loss channel and the determination of conditions when the axial heat flux can be suppressed to an acceptable level for fusion applications of open traps.

Investigation of plasma parameters in the expander regions is the key issue in this field of research. In a series of experiments at the GDT device in Budker Institute of Nuclear Physics, we measured local plasma potential and mean electron energy in the expander region by single Langmuir probe [5], which was the main instrument to investigate population of electrons existing between magnetic plug and the end plate.

Signals from the probe were measured related to the end plate, which can be biased by several hundred volts for realization of "vortex confinement" [6] mechanism of plasma stabilization if necessary. Under such conditions signal of potential measured by the probe fluctuates with frequencies of about 100 kHz and becomes inapplicable for further processing. For this reason completely galvanicaly isolated scheme was developed which allows for two types of measurements: measuring the plasma potential in the emission probe mode, as well as measuring the current-voltage characteristics of the probe, followed by calculating the plasma potential and the average electron energy.

In the Langmuir probe mode with a measurement of its current-voltage characteristic, the temporal resolution is 100 μs, the measurement range of the average electron energy is 0.5–50 eV, the measurement range of the plasma potential is ±100 V. In the emission probe mode, the plasma potential measurement range is ±1000 V, and the temporal resolution is about 1 μs. The developed diagnostics has been successfully used in experiments to study physical processes that determine the axial loss of particles and energy in open-type magnetic traps. Diagnostics can also be used in many areas where measurements with a single probe in a low-temperature or warm plasma need to be made relative to plasma electrodes with a fluctuating electric potential.

The features of the system consisting of the probe, electrical scheme and analog-to-digital converter (ADC) are described in this paper.

2 Experimental setup

Gas Dynamic Trap is an axially symmetric magnetic mirror machine [7]. The main part of the device is a 7 m long solenoid, with a magnetic field at the midplane up to 0.35 T and a mirror ratio $R = 35$. The GDT facility is intended for the confinement of plasmas with two ion components. One component is deuterium plasma with an isotropic Maxwell velocity distribution. This plasma has electron and ion temperatures of up to 250 eV and a density of ~ 1–3×10^{19} m^{-3} and is confined in a gas dynamic mode. Confinement of such plasma in the GDT is similar to that of a gas in a bottle with a small hole. The particle lifetime in the GDT is about $\tau_{\|} = L \cdot R/V_i$, where L is the trap length, R is the mirror ratio, and V_i is the ion thermal velocity. Another component consists of fast deuterons with an average energy of $\sim$ 10 keV and density up to 5×10^{19} m^{-3}. These ions are produced by intense deuterium neutral beam injection (NBI) of 5 ms duration, 22–25 keV particles energy and 5 MW power. This component is confined in adiabatic mode. Additional ECR heating allows the increase of the background electron temperature up to 900 eV [8]. The ECRH system is built upon two 54.5 GHz gyrotrons with a total incident power of up to 0.7 MW, in addition to the main heating power from the neutral beams.

In the series of experiments described below, plasma parameters of moderate range have been chosen: electron temperature on the GDT axis of about 150 eV, plasma density 1.4×10^{13} cm^{-3}.

A single Langmuir probe was used for measurements of the plasma potential in the vicinity of the movable plasma collector. The probe was made as a loop of thoriated tungsten wire with a diameter of 0.12 mm and a loop length of 7 mm. The distance between the probe and the collector was 90 mm. The probe could be operated as a classical biased Langmuir probe and as an emissive probe [9–11], heated by an external heating power supply. The probe in the emissive mode allows direct measurements of the local plasma potential. The plasma potential may also be derived from probe characteristics in the biased Langmuir mode. The task of derivation of electron distribution function is quite complicated in plasma with temperatures higher than in gas discharge. However, developed measurement system allows to obtain distribution function even in highly fluctuated plasma of GDT device.

The movable plasma collector with a Langmuir probe was installed in the expander tank opposite to the plasma gun. The variation of the expansion ratio was provided by moving the plasma collector axially (figure 1).

Figure 2 shows the principal scheme of probe operation. It provides two operational modes — "sawtooth" mode and "floating potential" emissive mode. In "sawtooth" mode voltage on the probe is a sum of DC voltage (positive or negative optionally with amplitude up to 150 V) and sawtooth

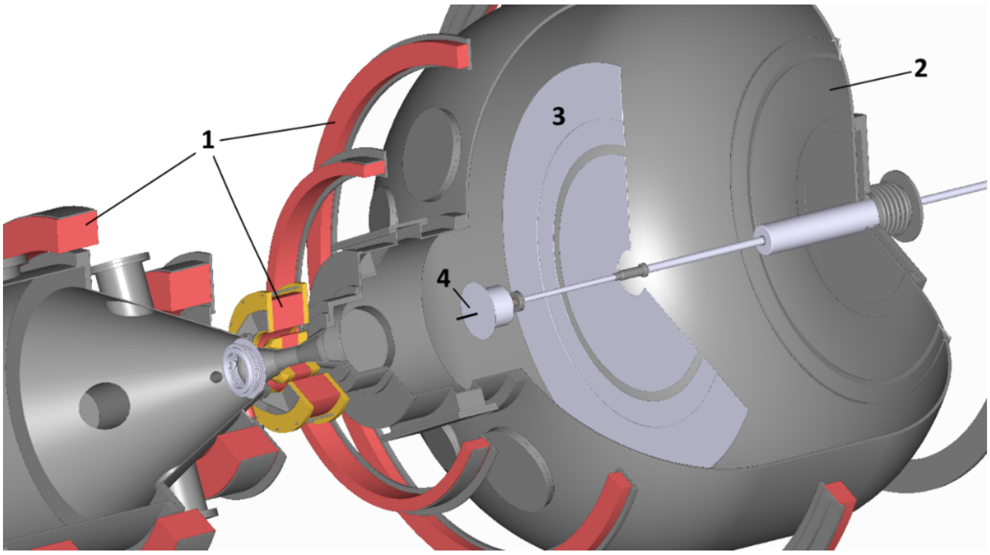

Figure 1. GDT expander: 1 — Magnetic coils, 2 — Western expander tank, 3 — End plate, 4 — Central movable part of end plate with embedded Langmuir probe.

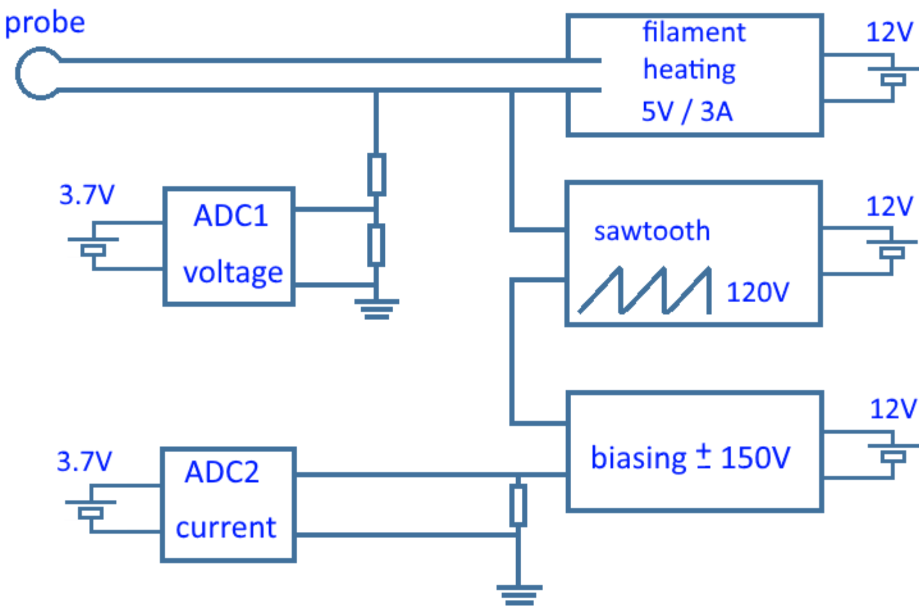

Figure 2. Scheme of the probe operation.

voltage with the duration of the rise 100 µs and fall 2 µs and amplitude up to 120V. Before the work impulse probe is heated by 3A current up to temperature of 600 K to clean its surface. Power supply system of the probe is grounded to the installation case. All communications for operation and control are carried out via fiber-optic channels, the power supply of separate circuit nodes is provided by batteries.

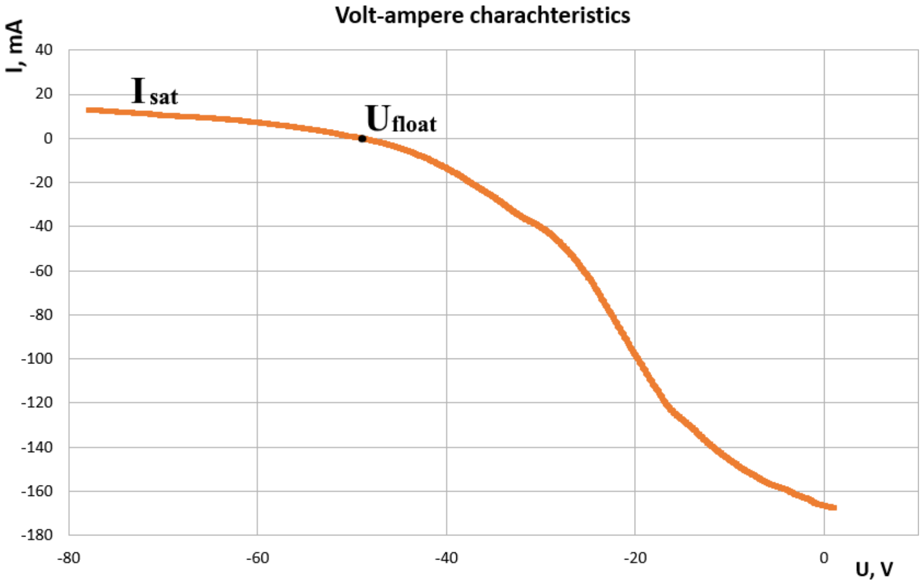

Figure 3. U-I characteristics obtained by emissive probe in "sawtooth" mode. Typical points indicated: I_{sat} — ion saturation current, U_{float} — floating potential.

3 Data proocessing

Scheme described allowed minimizing the influence of induced noises on the probe signals and obtain U-I characteristics suitable for further processing. Figure 3 demonstrates typical probe characteristics obtained from one cycle of "sawtooth".

Such a signal is approximated by quadratic function and then differentiated twice to apply Druyvesteyn method [12]. According it, current second derivative is proportional to distribution function of electrons in terms of energy:

$$\frac{\mathrm{d}^2 I}{\mathrm{d}U^2} \sim \frac{f_e}{E},$$

where $E = e(U_{\text{pl}} - U)$ is energy of the electron, U_{pl} is plasma potential defined as a point of first derivative maximum (or where second derivative equal zero). Energy scale of distribution function starts from this point. Density differential via energy is

$$\mathrm{d}n_e = f_e \cdot \mathrm{d}^3 v \sim \frac{f_e}{\sqrt{E}} \cdot \mathrm{d}E \sim \sqrt{E} \cdot I'' \mathrm{d}E,$$

where v is electron velocity. Figure 4 shows first and second derivative functions obtained from U-V characteristics (two curves have common axis, first derivative values are divided by factor of 10 for scaling). The first derivative curve has maximum at potential of $U_{\text{pl}} = -22\,\text{V}$. The second derivative multiplied by square root of energy is a required electron distribution function (figure 5). It demonstrates presence of two populations of electrons in the plasma: cold electrons with mean energy $\langle E \rangle \approx 5\,\text{eV}$ and warm electrons heated up to $20\,\text{eV}$. The mean energy of electrons is calculated as

$$\langle E \rangle = \frac{\int E^{\frac{3}{2}} I'' \mathrm{d}E}{\int E^{\frac{1}{2}} I'' \mathrm{d}E},$$

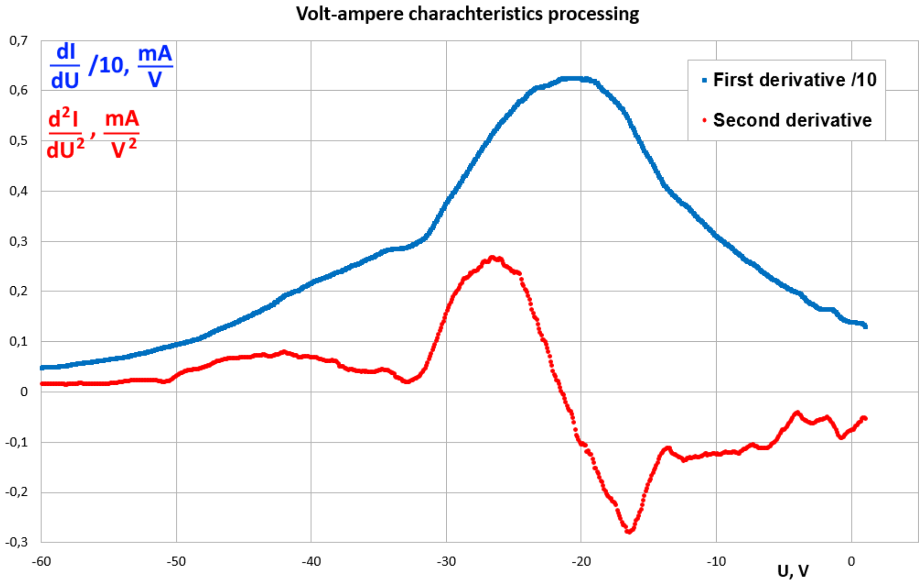

Figure 4. First derivative function divided by factor of 10 and second derivative function via energy of electron.

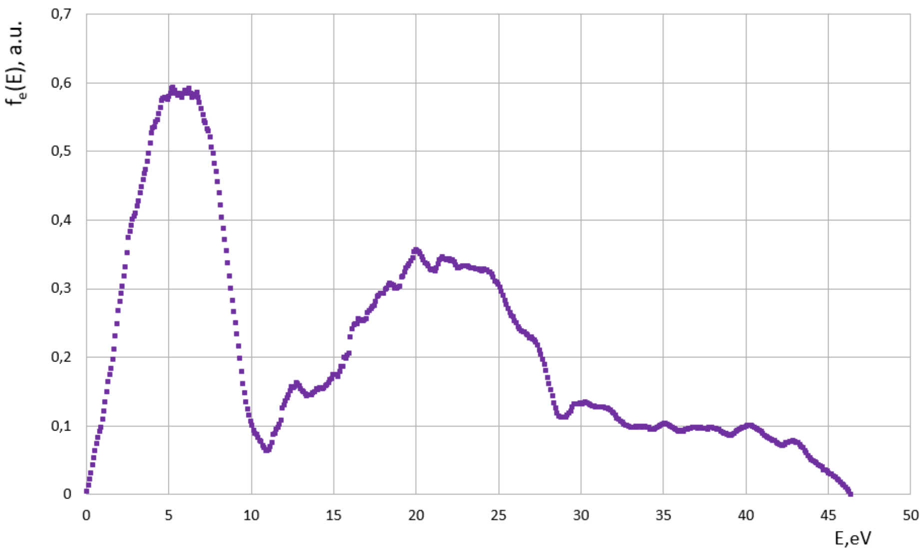

Figure 5. Electron distribution function obtained by Druyvesteyn method [12].

which gives the result $\langle E \rangle \approx (22,8 \pm 4,5)$ eV. This value is much lower than electron temperature in the central cell of GDT device (150 eV) as it had been predicted theoretically [13].

In "floating potential" mode the scheme unit responsible for the biasing and sawtooth is switched off. Before the pulse probe is heated up to emission temperature of 2000 K. The plasma potential is measured directly [10]. To avoid influence of measuring resistor on results the high impedance isolation amplifier (OP37) is used in the scheme.

4 Data recording module

Considering that the signal from the probe is measured relative to the central plate of the plasma absorber, which may be at some potential, there is a need for a galvanicaly isolated signal registrar. As a solution, a measuring subsystem was designed in Budker Institute, consisting of three basic elements:

- Small-sized two channel data recording module with low power consumption and built-in switching power supply;
- Digital bidirectional fiber optic communication line;
- Interface module to the system bus.

Within the framework of such a recording path structure, the measurement module is physically located near the probe, providing the best conditions for correct processing of the input signal. Working cycle of data recording module consists of several stages: firstly, power is on by external trigger coming from GDT controlling system, then the signal is digitized by fast ADC and stored in on-board memory, and finally transmitted to data base by optic line, after that power is off.

The isolation problem is solved by using digital optical fiber paths, and the task of interfacing with the system bus rests on the interface module located in any crate hub. The selected ADC (AD9220) provides 10 MHz sampling rate and incoming frequency range up to 10 MHz either. Input channels are equipped with operational amplifiers, which provide switchable input range ± 1.6 V, ± 0.8 V, ± 0.4 V. Used programmed logic array has small dimensions about 20×20 mm. Compact rechargeable battery provides power supply of ± 3.2 V with 1250 mAh of energy storage capacity. Battery is switching on during the work cycle only, thus power consumption is low enough for 2–3 months of work between charging. There are 48 Mb SRAM inside the module for fast data acquisition. Interface module can serve eight such ADC modules by TCP/IP protocol, each ADC has its own trigger adjustment.

Summarizing all features one can say that data recording module is quite small ($80 \times 110 \times 35$ mm), fast enough for specified task of mean electron energy measuring and completely decoupled to avoid stray fluctuations.

5 Conclusions

The complicated task of registration of U-I characteristics in highly fluctuated plasmas was solved at GDT device successfully by implementation of combined technique including electric scheme with appropriate parameters and galvanicaly decoupled registrar. Such approach to the measurements by single Langmuir probe can be useful for different modern plasma devices.

Acknowledgments

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2020 JINST 15 P01018