Real-time vertical plasma position control using the heavy ion beam diagnostic

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Abstract—A future thermonuclear fusion reactor relies on the real-time control of, for instance, instabilities and plasma position. At the tokamak ISTTOK, a novel approach of a real-time diagnostic system to measure and control the vertical plasma position (in a 100 μs closed-loop) was implemented by: (i) developing the Heavy Ion Beam Diagnostic (HIBD) to perform the position measurement and (ii) combining data processing on a FPGA and MARTe software framework. The preliminary results of this implementation have demonstrated the successful control of the plasma position using the HIBD. As a result, it was proved that the HIBD can be used to measure the ISTTOK vertical plasma position and feedback it in real-time. In this paper, the overall implementation and integration will be described and the preliminary experimental results presented.

Index Terms—HIBD, real-time, control, tokamak, vertical plasma position, FPGA, MARTe framework.

I. Introduction

TOKAMAKS are the most promising machine concept for a future controlled thermonuclear fusion reactor. Their successful operation relies on the real-time control of several parameters, including the plasma position. Such control consists on the measurement, data acquisition & processing and actuation. The control must be performed in real-time to prevent the degradation of the plasma conditions or the premature discharge termination, for instance due to vertical displacement events (VDEs - lost of the plasma vertical position control) or disruptions (fast and uncontrolled termination of the discharge) that may compromise the machine integrity. This paper presents a real time diagnostic system implementation for the control of the vertical plasma position at the tokamak ISTTOK using the Heavy Ion Beam Diagnostic (HIDB).

ISTTOK is an iron core tokamak with a major radius (R) of 0.46 m, minor radius (a) of 0.085 m and a typical toroidal field of ~ 0.5 T. The typical plasma parameters are a plasma current of 4×10^3 A and an averaged line density (passing at $r = 0$) of $5 \times 10^{18} \text{m}^{-3}$. The plasma position is controlled by magnetic fields generated on external coils. The current flowing into the coils is real-time controlled using the new ISTTOK control system [1], [2], [3]. The system has a control cycle of 100μs during which it reads all the diagnostics

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connected to the Advanced Telecommunications Computing Architecture (ATCA) digitizers and sends the control reference to ISTTOK actuators. The controller algorithms are executed on an Intel Q8200 chip with 4 cores running at 2.33 GHz and connected to the I/O interfaces through an ATCA based environment. The real-time control system is programmed in C++ on top of the Multi-threaded Application Real-Time executor [4].

Several diagnostics are used on ISTTOK for plasma position control: Mirnov coils (magnetic & integrated measurement), Langmuir probes [5] (electric & local measurement only at the periphery) and tomography (light radiation & integrated measurement). The HIBD measures locally and simultaneously the plasma parameters (convolved density and temperature which is a proxy for the plasma pressure) at 12 sample volumes vertically distributed along the central region of the plasma (-0.06 m $< r <$ 0.06 m) covering around 70% of the total diameter. Due to the nature of the HIBD measurements, it is expected a more accurate plasma position measurement than with the previous mentioned diagnostics. The novelty of this work is the use of the HIBD for the real-time control of the plasma vertical position.

The main challenge with this real-time implementation is the processing of the HIBD data. In order to have high signal to noise ratio on the vertical plasma position measurement, the background on the HIBD signals must be removed in every real-time cycle (100 μs). This paper presents a solution for this real-time implementation by using a fast data acquisition system and a combined data processing.

The second section of this paper explains how the vertical position measurement is performed using the HIBD. The third section presents the solution to the problem of processing the HIBD data in real-time. The fourth section consists on the preliminary results. Finally, the last section is a summary stating also some possible future improvements.

II. Measurement: The heavy ion beam diagnostic

ISTTOK vertical plasma position measurement is performed with the heavy ion beam diagnostic. The basic operation of the HIBD consist of the injection of a Xe^+ beam (primary beam) in to the plasma and collection of the Xe^{2+} beams (secondary beams). The secondary beams are generated into the plasma by the single ionization of the primary beam due to the impact with the plasma electrons. The double charged ions and the strong (toroidal) magnetic field of the tokamak separate the secondary beam trajectory from the primary one allowing a spatial discrimination. By using a Multiple Cell Array

Detector (MCAD) [6] to collect the secondary ion beams, the detector cells will geometrically corresponds to a sample volume into the plasma. The current installed MCAD allows to measure locally and simultaneously 12 sample volumes along the primary beam trajectory in a plasma region of roughly -0.06 m $< r <$ 0.06 m, as illustrated by Fig.1, [7].
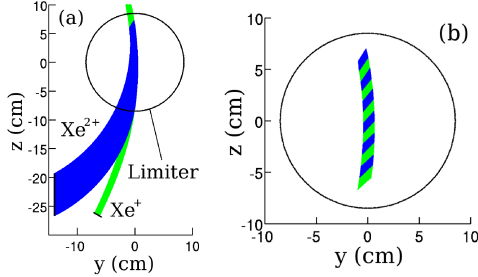

Fig. 1. Illustration of the: (a) Primary Xe^+ and secondary Xe^{2+} ion trajectories and (b) sample volume location inside the plasma.

This diagnostic measures the $n_e\sigma_{eff}(T_e)$ product: the plasma density (n_e) times the effective ionization cross-section of the Xe^+ single ionization ($\sigma_{eff}(T_e)$). The $\sigma_{eff}(T_e)$ is a known function which depends on the electron temperature (T_e). For ISTTOK plasma electron temperature range, the $\sigma_{eff}(T_e)$ is a monotonically increasing function and therefore the $n_e\sigma_{eff}(T_e)$ product can be regarded as a proxy for the plasma pressure. Since the plasma equilibrium is related with the plasma pressure, it is expected that the $n_e\sigma_{eff}(T_e)$ will give an accurate measurement for the plasma position.

The plasma vertical position (Z) is be calculated from the $n_e\sigma_{eff}(T_e)$ profile by taking its "centre of mass". The equation is:

$$Z = \frac{\sum_{i=1}^{12} n_e(z_i)\sigma_{eff}\big(T_e(z_i)\big) \cdot z_i}{\sum_{j=1}^{12} n_e(z_j)\sigma_{eff}\big(T_e(z_j)\big)} \qquad (1)$$

where z_x is the vertical position of the sample volume number x, obtained from the geometrical reconstruction of the beam trajectories.

A. Signal conditioning

In order to have an increased signal to noise ratio, the primary beam is chopped at a high frequency to allow the discrimination of the beam signal from the background noise signal. The higher the chopping frequency the better the fast background noise changes can be taken into account and then removed. In this way, the HIBD was upgraded by increasing the amplifier system bandwidth [7] and chopping frequency allowing now a fast chopping up to 150 kHz as shown in Fig.2.

The HIBD can provide one profile per chopping period. This means that with a chopping frequency of 150 kHz it is possible to obtain up to $n_e\sigma_{eff}(T_e)$ 15 profiles in one ISTTOK real-time cycle (100 μs). In order to obtain at least one new $n_e\sigma_{eff}(T_e)$ profile per real-time cycle it is necessary to chop the ion beam at a frequency higher than 10 kHz.
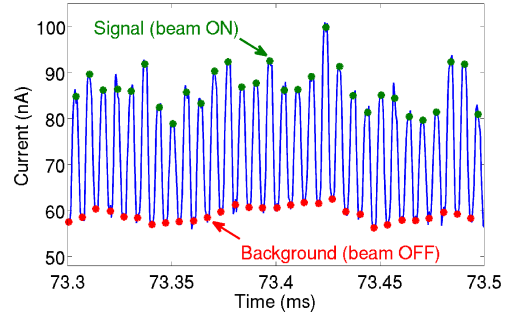

Fig. 2. HIBD typical signal chopped at 150 kHz. The real (cleaned) beam current is obtained by subtracting the red dots to the corresponding green ones.

III. Solution: Data acquisition and combined processing

This real-time diagnostic implementation was performed by using a fast data acquisition and combined processing with: galvanic isolated digitizer modules together with a Field Programmable Gate Array (FPGA) on a ATCA system [8] and MARTe framework.

An overall view of the implementation is presented in Fig.3. One whole real-time closed loop cycle can be described as:

- The HIBD injects the primary ion beam;
- The primary ion beam is ionized into the plasma and generates secondary ion beams;
- The secondary ion beams are collected in the HIBD detector generating an electrical current;
- The electrical currents are amplified and converted to voltage signals with the Amplifiers;
- The signals are acquired by the ADCs (Analog to Digital Converters) in the ATCA data acquisition system;
- The FPGA removes the background from the HIBD signals;
- The HIBD Generic Application Module (GAM) calculates the vertical position;
- The PID controller GAM receives the vertical position and feedbacks to the power supply controller (actuator);
- The actuator guarantees that the requested current is flowing into the horizontal field coils;
- The current flowing in the coils creates a horizontal magnetic field that will change the vertical plasma position.

The HIBD data is sampled at rate of 2Msps by the ADCs. The FPGA collects the sampled data and performs the necessary processing to remove the background noise. Every real-time cycle, the FPGA returns a clean signal (one for each of the 12 HIBD sample volumes) corresponding directly to the secondary ion beam current. The signals are then sent to MARTe and used by the HIBD GAM to calculate the $n_e\sigma_{eff}(T_e)$ profile. Once the profile is calculated the GAM calculates the vertical plasma position and returns the result to the PID controller GAM.

A. The FPGA

The Field Programmable Gate Array performs the core processing of this real-time implementation. In order to correctly
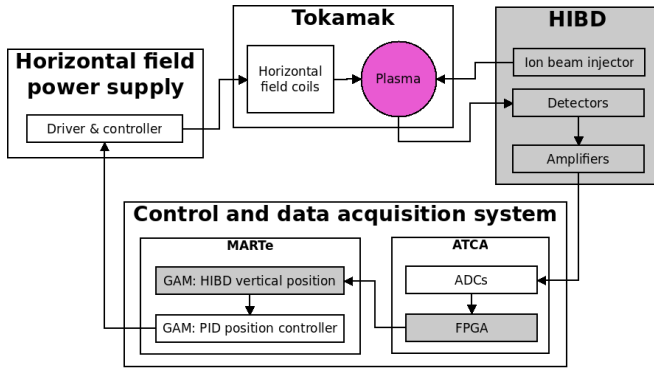
Fig. 3. Simplified diagram of the HIBD closed loop integration for plasma vertical position measurement and control. GAM stands for Generic Application Module. The grey boxes represent the performed changes and additions related to the ISTTOK control and feedback system.

obtain and process a new $n_e\sigma_{eff}(T_e)$ profile the HIBD data must be averaged to reduce the statistical error and somehow filter the signal. Such processing must be performed in a much faster time scale than the ISTTOK real-time cycle and it should use the maximum quantity of sample points acquired during one real-time cycle. These requirements were only possible to satisfy by using the FPGA.

Fig.4 shows an illustration of the implemented algorithm that removes the background noise. It consists on the following steps:

- Detect a transition on the reference signal of the ion beam chopping (red slices on Fig.4);
- Wait a predefined number of samples (corresponding to the delay between the reference signal and the acquired secondary beam currents);
- Perform the summation of another predefined number of samples corresponding to a ON or OFF region (green or blue slices in Fig.4, respectively);
- Return the difference from the previous summation taking into account if it is a ON or OFF region. The division to obtain the average value is only performed in the HIBD GAM.
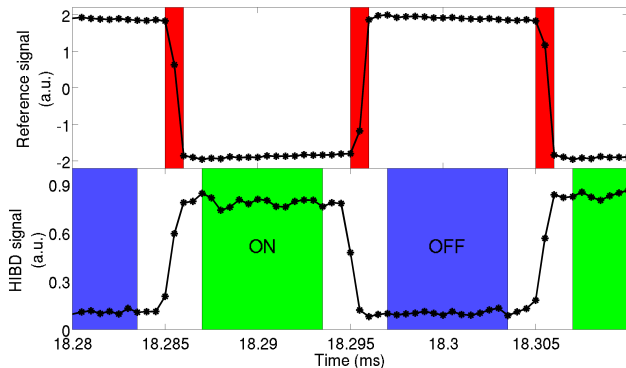

Fig. 4. Red time slices (upper plot) correspond to the transition detections while green and blue time slices to the ON and OFF summations of the predefined number of samples (bottom plot).

Because of the non synchronization between the ion beam chopping frequency and the MARTe real-time cycle, and to

guarantee a whole chopping period within one real-time cycle (beam: OFF-[ON-OFF]-ON or ON-[OFF-ON]-OFF during one cycle), the ion beam chopping frequency had to be chopped at a frequency higher than 15 kHz. The chosen frequency was 16 kHz which is just above the minimum frequency but still slow enough to guarantee a good averaging (more samples to be averaged).

B. MARTe - The HIBD GAM

The Multi-threaded Application Real-Time executor is a control C++ modular framework designed for real-time projects, providing an easy way of deploying, configuring, and connecting real-time algorithms, together with a hardware interfacing abstraction layer. It is built upon a C++ multiplat-form real-time library named BaseLib2. The atomic element of MARTe is named Generic Application Module, and all applications built using the framework are designed around these elements. A GAM is a block of code implementing an interface specified in the BaseLib2 library. The core of a typical GAM processes the input accordingly to how it was configured and outputs the modified information [4].

The HIBD GAM contains the algorithms for the calculation of the $n_e\sigma_{eff}(T_e)$ profile and the plasma vertical position. The $n_e\sigma_{eff}(T_e)$ profile is calculated using the simple inversion method described in [9]. The plasma vertical position is calculated using (1). The GAM execution time takes usually less than 0.5 μs.

A GAM configuration allows to change parameters, some of them related with the execution code, without having to recompile the GAM code. These parameters can be changed on the MARTe config file. Among the several HIBD GAM configuration parameters, it is relevant to mention here some of them:

- *Injected primary beam current*: The injected primary beam current, which is used for the calculation of the $n_e\sigma_{eff}(T_e)$ profile, may vary depending on the diagnostic configuration (for instance, due to changes on the beam energy). This parameter allows to change the value of the injected beam current.
- *Vertical positions*: The location of the sample volumes changes in accordance to the beam energy and angle of injection. This parameter is a vector and allows to set the vertical location of all the sample volumes.
- *Minimum threshold for the total $n_e\sigma_{eff}(T_e)$*: When the total $n_e\sigma_{eff}(T_e)$ (integral of the profile) is below the minimum threshold the calculation of the vertical position is not performed and the GAM returns 0.
- *Output calibration*: a linear calibration (multiplication factor and offset) can be applied to the plasma vertical measurement value.

IV. PRELIMINARY RESULTS

Before using the HIBD to feedback the plasma vertical position, the testing and calibration were performed during real discharges: the whole system was working as it would be in its final state but, with the only difference of not performing the position feedback to the controller. Once all the tests

and calibrations were performed, the position from HIBD measurements was feedback to the PID controller. The PID controller was tuned in order to optimize the system response.

Fig.5 presents some preliminary results for the ISTTOK shot number 39813. It is observed that the measurement follows relatively well the set-point. A good qualitative agreement was also observed when comparing the HIBD measurement with the other ISTTOK plasma position measurement diagnostics. Such results together with the successful plasma position control (without disruptions due to the loss of the vertical position) demonstrate the successfulness and quality of the overall real-time implementation.
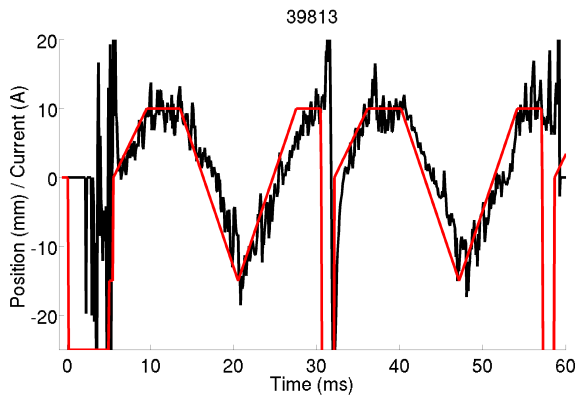

Fig. 5. The red line is the set-point and the black line is the vertical plasma position measured by the HIBD. On the instants where the red line is below -20 the feedback on the plasma position is switched off and the horizontal field coils are in current feed forward.

V. SUMMARY AND FUTURE WORK

A novel real time diagnostic system implementation for the control of the vertical plasma position was performed at the tokamak ISTTOK using the Heavy Ion Beam Diagnostic. This implementation was performed by using a fast data acquisition and combined processing system composed of: galvanic isolated digitizer modules and a FPGA on an ATCA system, and MARTe framework. The FPGA was used to process the 2Msps acquired HIBD data and provide a clean signal to the real-time framework every 100 μs (real-time cycle). The HIBD Generic Application Module was programmed to calculated the $n_e\sigma_{eff}(T_e)$ profile and the vertical plasma position from the "Centre of Mass" of the profile. Preliminary results have been obtained and have demonstrated the successfulness of the real-time diagnostic system implementation.

Further improvements are expected to be performed in terms of the vertical plasma position measurement filtering, for instance using a Kalman filter. The aim of filtering the signal is to remove/smooth high frequencies that are faster than the system response. The use of an adaptive PID controller is also under consideration. The aim of both these improvements will be the use of a harder PID controller to improve the control speed and quality.

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