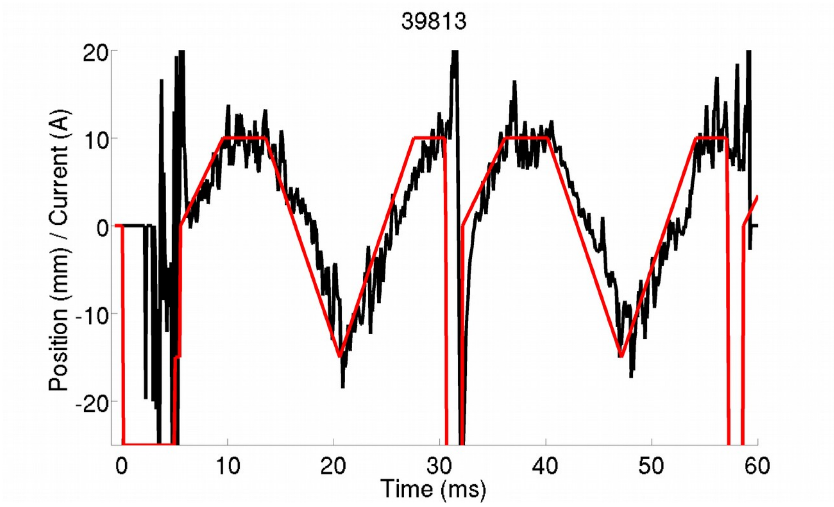
Real-time vertical plasma position control using the heavy ion beam diagnostic



Rafael B. Henriques
rhenriques@ipfn.tecnico.ulisboa.pt

Poster # 097

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

Rafael B. Henriques*, Bernardo B. Carvalho, André S. Duarte, Ivo S. Carvalho, António J. N. Batista, Rui Coelho, Carlos Silva, Artur Malaquias, Humberto Figueiredo, Hugo Alves, Horácio Fernandes and Igor S. Nedzelskiy

*rhenriques@ipfn.tecnico.ulisboa.pt

Instituto de Plasmas e Fusão Nuclear, Instituto Superior Técnico, Universidade de Lisboa, 1049-001 Lisboa, Portugal

Introduction & Motivation

Introduction

A novel approach of a real-time diagnostic system to measure the vertical plasma position (100 µs cycle) was implemented at the tokamak ISTTOK by developing the Heavy Ion Beam Diagnostic (HIBD) to perform the plasma position measurement.

The motivation of this work is to prove this new concept which has never been performed in magnetic confinement nuclear fusion devices.

Tokamak ISTTOK:

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 5×10^{18} m^{-3}.

Measurement: HIBD

Measurement

Heavy Ion Beam Diagnostic (HIBD):

- Performs local and simultaneous measurement of $n_e\sigma_{eff}(T_e)$ product in 12 sample volumes along the primary beam trajectory covering ~70% of the plasma diameter [1], Fig.1
- $n_e\sigma_{eff}(T_e)$ product is a proxy for plasma pressure
- Due to HIBD measurement nature, a more accurate plasma position is expected than with typical ISTTOK real-time plasma position diagnostics:
  - Mirnov coils (magnetic & integrated measurement)
  - Langmuir probes [2] (electric & local measurement at the periphery only)
  - Tomography (light radiation, integrated measurement & reconstruction)
- Vertical plasma position is calculated from the "Centre of Mass" of the $n_e\sigma_{eff}(T_e)$ profile:

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

Problem / challenge with the real-time implementation

Problem with real-time implementation:

- In order to obtain a high signal to noise ratio measurement, the primary beam should be chopped at a high frequency, Fig.2
- Background noise must be removed faster than the real-time cycle, but signal averaging is necessary

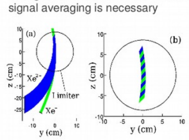


Fig.1: **(a)** Primary (Xe^{+}) and secondary (Xe^{2+}) beam trajectories; **(b)** Sample volumes

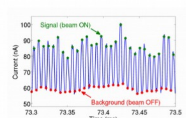


Fig.2: HIBD secondary beam signal chopped at 150 kHz

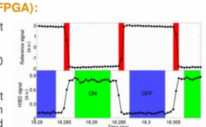
Solution: Fast data acquisition & Fast combined data processing

Implementation (solution)

Use a **fast data acquisition and combined processing** with: galvanic isolated digitizer modules together with a Field Programmable Gate Array (FPGA) on a ATCA system [3] and MARTe framework [4].

Field Programmable Gate Array (FPGA):

- Processes the HIBD data acquired at 2Msps
- Allows the averaging of up to 200 samples / real-time cycle (100 µs)
- By chopping the primary ion beam at a frequency > 15 kHz, the FPGA can remove the background noise and provide a new cleaned signal every real-time cycle



Red slices are the transitions on the chopping reference signal. The averaging is performed during the ON and OFF regions.

Implementation: FPGA on ATCA system & MARTe framework

MARTe :

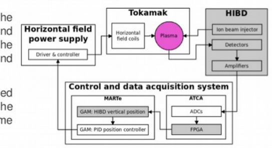
Multi-threaded Application Real-Time executor (MARTe) is a control C++ modular framework designed for real-time projects. The atomic element of MARTe is the GAM. The core of a typical GAM processes the input accordingly to how it was configured and outputs the modified information [4].

- **HIBD GAM:**
  - Receives the data from the FPGA and calculates the $n_e\sigma_{eff}(T_e)$ profile
  - Calculates and return the vertical plasma position
  - Configuration (relevant parameters):
    - Injected primary ion beam current
    - Vertical positions of the sample volumes
    - Output calibration

Overall implementation

Overall real-time closed loop implementation:

- Grey boxes represent the performed changes and additions related to the typical ISTTOK control and feedback system [5]
- ISTTOK real-time closed loop takes 100 µs, but the HIBD GAM execution time is < 0.5 µs

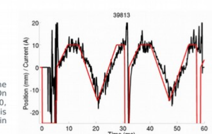


Results

Results

The result in the figure together with the successful plasma position control (without early termination of the discharge due to the loss of the vertical plasma position) has demonstrated the quality and success of the overall real-time implementation.

Red line is the set-point and black line is the vertical plasma position measured by 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 control.



Summary & Future work

Summary & future work

- A successful 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 new implementation allowed to have a better and more accurate control in a wider range of the vertical plasma position
- Further improvements are expected to be performed in terms of:
  - vertical plasma position measurement filtering, for instance using a Kalman filter
  - use of an adaptive PID controller (under consideration)
- The aim of both these improvements will be the use of a harder PID controller to improve the control speed and quality

References:

[1] R. B. Henriques, A. Malaquias, I. S. Nedzelskiy, C. Silva, R. Coelho, H. Figueiredo, and H. Fernandes, "Radial profile measurements of plasma pressure-like fluctuations with the heavy ion beam diagnostic on the tokamak isttok," Rev. Sci. Instrum., vol. 85, p. 11D848, Aug. 2014

[2]I. S. Carvalho, H. Fernandes, P. Duarte, C. Silva, H. F. C. Figueiredo, and T. Hekkert, "Isttok real-time control assisted by electric probes," Journal of Physics, vol. 591, p. 012008, 2015

[3]A. J. N. Batista, A. Neto, M. Correia, A. M. Fernandes, B. B. Carvalho, J. C. Fortunato, J. Sousa, C. A. F. Varandas, F. Sartori, and M. Jennison, "Atca control system hardware for the plasma vertical stabilization in the jet tokamak," IEEE Trans. Nucl. Sci., vol. 57, pp. 583–588, Apr. 2010

[4]A. C. Neto, F. Sartori, F. Piccolo, R. Vitelli, G. D. Tommasi, L. Zabeo, A. Barbalace, H. Fernandes, D. F. Valcrcel, A. J. N. Batista, and J.-E. CONTRIBUTORS, "Marte: A multiplatform real-time framework," IEEE Trans. Nucl. Sci., vol. 57, pp. 479–486, Apr. 2010

[5]I. S. Carvalho, P. Duarte, H. Fernandes, D. F. Valcrcel, P. J. Carvalho, C. Silva, A. S. Duarte, A. Neto, J. Sousa, A. J. Batista, and B. B. Carvalho, "Isttok control system upgrade," Fus. Eng. and Des., vol. 88, p. 11221126, Oct. 2013

Acknowledgement: IPFN activities received financial support from "Fundação para a Ciência e Tecnologia" through the project UID/FIS/50010/2013.

FCT Fundação para a Ciência e a Tecnologia

Final remark

The use of a Heavy Ion Beam Diagnostic for the real-time plasma position control has never been performed in nuclear fusion devices

Poster # 097

ipfn
INSTITUTO DE PLASMAS
E FUSÃO NUCLEAR