Real-time plasma control based on the ISTTOK tomography diagnostic[a)]

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The presently available processing power in generic processing units (GPUs) combined with state-of-the-art programmable logic devices benefits the implementation of complex, real-time driven, data processing algorithms for plasma diagnostics. A tomographic reconstruction diagnostic has been developed for the ISTTOK tokamak, based on three linear pinhole cameras each with ten lines of sight. The plasma emissivity in a poloidal cross section is computed locally on a submillisecond time scale, using a Fourier–Bessel algorithm, allowing the use of the output signals for active plasma position control. The data acquisition and reconstruction (DAR) system is based on ATCA technology and consists of one acquisition board with integrated field programmable gate array (FPGA) capabilities and a dual-core Pentium module running real-time application interface (RTAI) Linux. In this paper, the DAR real-time firmware/software implementation is presented, based on (i) front-end digital processing in the FPGA; (ii) a device driver specially developed for the board which enables streaming data acquisition to the host GPU; and (iii) a fast reconstruction algorithm running in Linux RTAI. This system behaves as a module of the central ISTTOK control and data acquisition system (FIRESIGNAL). Preliminary results of the above experimental setup are presented and a performance benchmarking against the magnetic coil diagnostic is shown. [DOI: 10.1063/1.2955854]

I. INTRODUCTION

A real-time plasma position control system is required to achieve long duration (up to 250 ms), alternating Current (ac), discharges on the tokamak ISTTOK (R=0.46 cm, a=8.5 cm, t_D=30 ms, I_p=4 kA, B_T=0.5 T). Such a system has been in place for some time using magnetic probes.[1] However, this system has been found to be limited during the current inversion of ac discharges. A tomography diagnostic has been installed to supply additional feedback to the control system.

This paper presents the data acquisition and reconstruction (DAR) real-time system, based on ATCA technology and consisting of one acquisition board with integrated FPGA capabilities and a dual-core Pentium module running real-time application interface (RTAI) Linux. The Fourier–Bessel tomographic algorithm as well as the plasma positioning are described. These can both be processed in real time (one reconstruction in <0.1 ms).

II. SETUP

The DAR real-time system, based on ATCA technology, was developed in house. It uses two general purpose ATCA modules, one is an acquisition board and the other is an interface from a standard PC motherboard to the ATCA bus via the PCI-EXPRESS port (see Fig. 1).

The acquisition board provides 32 analog input channels and 8 analog output channels. It is an ATCA single width card comprising a main board, a carrier board, isolated analog-to-digital converter (ADC) or digital-to-analog converter (DAC) modules, and a rear transition module (RTM) mechanically connected together. Both types of analog I/O can be present on the carrier board and on the RTM. Up to 12 cards can be simultaneously inserted on an ATCA shelf.

The main board has a Xilinx XC4VFX60 field programmable gate array (FPGA), providing digital signal processing and a standard independent communications unit. A total of 15 RocketIO multigigabit transceivers (2.6 Gbits/s) connect the FPGA to the ATCA fabric channels, allowing full mesh topologies, plus one connected to the RTM. Connected to the FPGA are two memory modules, a SODIMM DDR2 with up to 512 mbytes and a COMPACT FLASH with up to 1 Gbyte of available memory.

The carrier board can be populated with up to 32 ADC or DAC modules. The ADC module consists of one differential analog input with a dynamic range of ±32 V, 18 bits resolution at 2 MSPS, a passive antialiasing filter and galvanic isolation.

The RTM consists of eight galvanically isolated DAC

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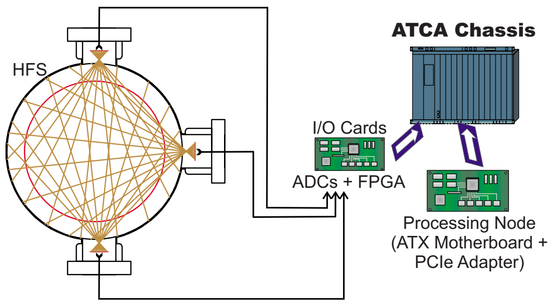

FIG. 1. (Color online) The tomography data acquisition ATCA system installed in ISTTOK. The 30 channels are acquired by the I/O card and relayed to the PC module via the ATCA bus.

channels, each with one differential analog output, a dynamic range of ± 10 V, 16 bits resolution at up to 50 MSPS, a passive reconstruction filter, and a fiber optic SFP port for high speed digital links to remote instrumentation.

The interface with the uATX/ATX PC motherboard is a double width ATCA blade comprising the motherboard itself, a carrier board, and a RTM mechanically connected together. The carrier board makes the interface between the ATCA fabric channels (times 4 full-duplex PCIE) and the PC motherboard (times 16 full-duplex PCIE) through PCI EXPRESS low latency switches. The RTM is a high efficiency power supply for the uATX/ATX PC motherboard. This unit can connect to 12 ATCA fabric channels (times 4 full-duplex PCIE), it has an Intel® Core2 Duo 6300 processor running at a clock speed of 1.86 GHz and a real-time operating system (RTAI for Linux), delivering high speed processing when requested.

The communication with the power supplies for the horizontal and vertical field coils is done at 781.25 kbaud, with only one cable for three different power supplies. Each current setpoint requires 20 bits of data to be transmitted, so three power supplies require 60 bits. Some spaces between bits are added for stability which results in one update of the setpoints every 128 μs. Since the acquisition of data is done at 2 MSPS, the data must be filtered and downsampled. This task is performed by the FPGA, in real time so that only one sample is provided to the tomography algorithm.

The ISTTOK tomography system consists of 30 photodiode channels, 10 in each of the three cameras. Each camera has a circular pinhole of 1 mm at 10 mm from the photodiode array, allowing a full coverage of the plasma. Each photodiode has a size of 1.5×1.5 mm^2. No filter is used so each photodiode is measuring visible light but mainly ultraviolet. Each channel is amplified by a transductance amplifier with a gain of 1.8×10^6.

In tomography, the goal is to generate a cross-sectional view of a given substance from a set of integrated measurements. The Fourier–Bessel reconstruction algorithm was adopted,[2] valuated as a good compromise between fast calculations and quality of the reconstruction. It essentially approximates the emissivity profile by a Fourier expansion on the poloidal plane and an expansion in Bessel functions in the radial direction. The Nyquist theorem states that the ten diodes per camera allow up to five radial modes and the three nonequidistant cameras allow up to two poloidal modes. In this work, the reconstructions are performed on a 15×15 pixel grid which takes advantage of the available resolution of the system.

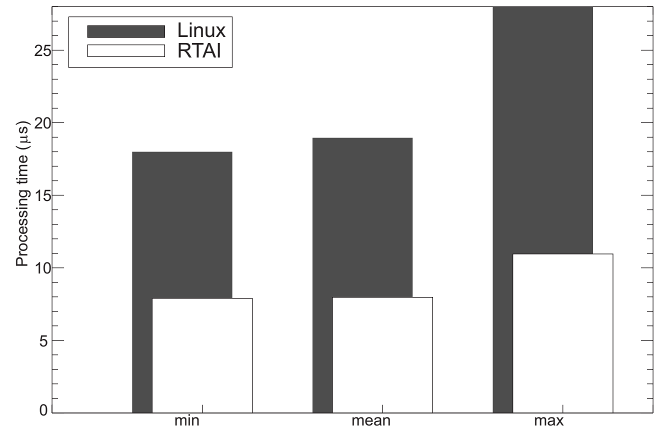

FIG. 2. Comparison of the time the tomography algorithm takes to complete a reconstruction and determine its center as a standard Linux application (gray) and as a RTAI module (white, faster and less jitter).

The plasma position is determined from the reconstructed emissivity by calculating its average center. If the emissivity presents a peaked or hollow profile, then this algorithm yields the correct position. If it presents an asymmetrical profile, then this position should only be approximate, but it will never be nonsensical as is the case with the positioning by the magnetic probes, when the plasma current is too low, which happens during plasma current reversal of ac discharges.

III. ANALYSIS AND DISCUSSION

The algorithm was coded in C and run under the real-time application interface (RTAI) layer for Linux. In order to have a fast algorithm, all calculations use long integer numbers and all that could be preprocessed was stored in matrices.

Figure 2 shows the time the tomographic algorithm takes to run as a standard Linux application and as a RTAI module. As expected, the latter is faster and presents less jitter. Given that the current supply to the horizontal and vertical field coils can only be updated every 128 μs, this task uses about 10% of the time to process, leaving the processor available for other tasks.

Figure 3 shows tomographic reconstructions of the emissivity and Poincaré maps of the current profile given by the 3D-MAPTOR code[3] for shot 16465. This shot was a two half cycle, flattop ac discharge, with 3.5 kA positive plasma current until 27 ms and with −3 kA negative current afterward. The symbols in the tomographic reconstructions show the plasma position given by the average center algorithm ($*$) and by the current filament algorithm ($\square$) applied to the magnetic probe data.[1] The agreement between the tomography and the 3D-MAPTOR codes is relatively good, considering they are measuring different physical quantities.

The presented DAR is based on two ATCA modules, one is the 32 channel acquisition board and the other is an interface from a standard PC motherboard to the ATCA bus via the PCI-EXPRESS port.

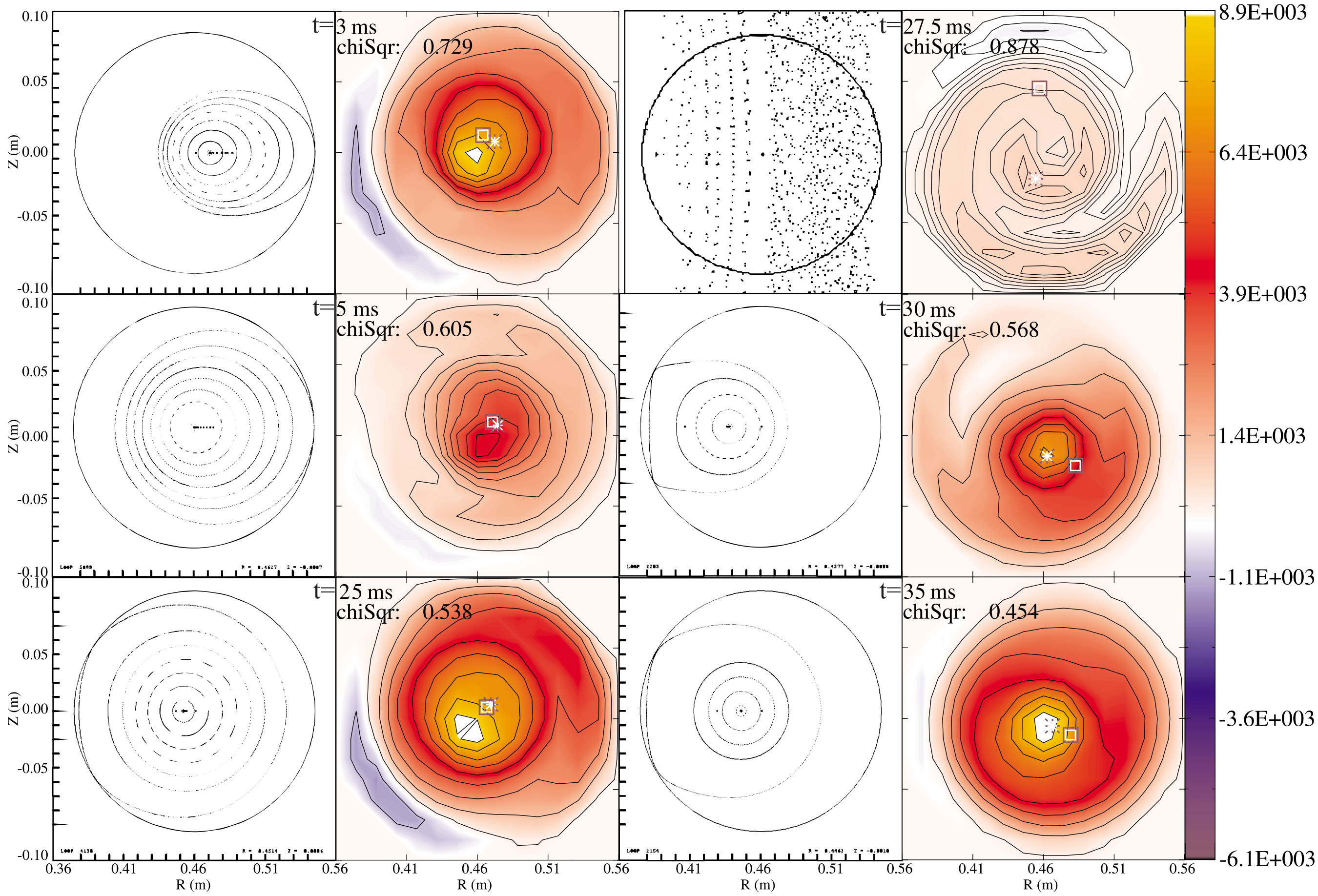

FIG. 3. (Color online) Tomographic reconstructions (right) and 3D-MAPTOR poincaré plots (left) for six instances of the shot 16465. The * symbol indicates the plasma position calculated by the average center of emissivity and the □ symbol indicates the plasma position calculated by the current filament algorithm from the magnetic diagnostic. At the start (t=3, 5 ms), both show a slightly outward plasma with a more peaked profile at 3 ms than at 5 ms. Just before the current reversal (t=25 ms), both show a slightly inward plasma occupying the whole vessel. Thus far, the plasma positions given by the current filament show a good agreement with the tomography's average center. During the reversal (t=27.5 ms), the 3D-MAPTOR code could not converge on a solution, due to very low plasma current, while the tomography presents a hollow profile, ignoring the artifacts present on the outer part of the reconstruction. The current filament method returns a position for the plasma that is excessively away from the center of the vessel. After the current reversal, 3D-MAPTOR shows the plasma clearly in the high field side (HFS) while the tomography shows it only slightly in the HFS and the current filament method positions it to the low field side.

The tomography system presented is both fast and reliable, yielding one reconstruction in an average of 8 μs, leaving the processor free for about 90% of the time. It is also in relative agreement with the 3D-MAPTOR code, validating it for further use in ISTTOK as a real-time plasma position diagnostic.

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