Data Acquisition and Digital Processing in Nuclear Fusion

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Abstract
This work concerns Data Acquisition and Digital Processing related to magnetic diagnostics currently used in Nuclear Fusion Research. The core of the work is the description of developed architectures in Verilog, used algorithms, the performed tests and the obtained results of acquisitions from ISTTOK’s Mirnov coils signals and made test assemblies. The used modules are galvanic isolated digital modules with signal chopper mode and a sampling at 2 MSPS (18-bit full precision data) developed by IPFN (Instituto de Plasmas e Fusão Nuclear, Lisbon).

Keywords: Nuclear Fusion, Data Acquisition, Digital Processing, ATCA, Integrator modules, Magnetic diagnostics

1. Introduction

1.1 - Fusion

Nuclear fusion powers the sun and the other stars and is a promising source of energy to support the increasing world demand. It consists on the light-z nuclei combination with the mass reduction of the products in comparison with the reagents and the consequent energy release. After a fusion reaction the “missing” mass is converted into energy and can quantified by the well-known Einstein equation:
\[ E = (m_r - m_p)c^2 \] (1)

In order to induce the fusion of two nuclei it is necessary to overcome the mutual repulsion due to their positive charges (the distances between reagents have to be small enough to have the nuclear force being bigger than the electrostatic forces). The most promising method of supplying the energy is to heat the reagents to a sufficient high temperature so that the thermal velocities of the nuclei are high enough to produce the required reactions. At these temperatures the fusion fuel will ionize and constitute a plasma.

There are only three studied plasma confinement methods possible to have nuclear fusion, the gravitational confinement, the magnetic confinement and the inertial confinement. On earth the most studied method that has given the best results is magnetic confinement, and nowadays the most used devise to achieve nuclear fusion by magnetic confinement is the Tokamak (Closed Toroidal Confinement System).

In tokamaks, stable and steady-state operation is still a challenging subject which has not yet been solved. In order to reach these goals, diagnostics will be more important not only for measuring plasma parameters but also for precise plasma control. [1]

1.2 – Magnetic Measurements

In Fusion investigation several types of magnetic diagnostics are used, which in most of the cases are composed by magnetic sensors such as inductors or conductor loops.

In tokamaks the magnetic diagnostics provide essential information as the main electromagnetic parameters of the plasma (plasma current $I_p$ and internal inductance $l_i$), the position or speed of the plasma current centroid and the shape of the plasma boundary. Information provided by magnetics is used in most machine control loops and by almost all other diagnostics. [2]

Some of the more simple examples of these devices are the Mirnov coils (fluctuations/instabilities) and the Rogowski coils (plasma current). In these types of diagnostics occurs an electromotive force induced on the devices that is originated by the variation of magnetic flux that passes by them over time. It is necessary to integrate the receiving signal/data during the acquisition to get a voltage that is proportional to the flux/magnetic field being measured.

1.3 - Integrator modules

The process of time integration has a well-known problem, defined as the “integrator problem”, caused by electronic noise and voltage offsets during acquisition of long periods of time (e.g. 1000 s). The consecutive integration of noise will influence the integral that is being constructed by leading its value to have an additional undesired error drift. At present, the developed integrators appear to be stable within 100 µV.s /1000s. [3]

It was been done a lot of effort to isolate the noise from the signals after or during the acquisition. One of the factors that influence the electronic noise is the temperature [4]. Measuring it through the acquisition will allow the compensation of this factor in real time.

In today’s tokamaks the integration of the incoming signals from magnetic diagnostics is done by devices that can be divided in analogic integrators and digital integrators.
The major advantage of analog electronic signal integration comparing to digital integration is the continuous signal output, which can be used directly as a flux measure and no further signal processing is needed. The circuit of an analog integrator is shown at Figure 2.

The analog integrator has its output range limited by its power supply (it can become saturated in the case of a high flux variation such as a disruption); it has a low dynamic range output comparing to the one of digital integration, which is determined by the input saturation level, the signal rise time, and the sample rate.

Analog integrators have other intrinsic problems as the integrator drift, due to the offsets of the operational integrator which introduces an absolute error that increases with integration time. In numerical integrators (the used module during this work can be seen in Figure 1) the digitized induction signal has to be integrated and corrected for offsets in time using digital signal processing, which uses algorithms that have major advantages with respect to offset corrections compared with sample and hold circuits (for analog integrators, Figure 2) when the input signal is noisy. [3] [5]

A simple schematic of a numerical integrator is shown in Figure 3.

The chopper, which is driven by a clock, switches the terminals of the incoming signals in a way that the integrator gets rid of most of the temperature dependence of the junctions and semiconductor characteristic.

2. Implementation

On this chapter it is described the global acquisition system used in this thesis. To perform this work it was been done modifications on previous used Firmware written in Verilog, drivers in C and the development of a software to assist the operator, a text based user-friendly interface. The used modules are galvanic isolated digital modules developed by IPFN with signal chopper mode and a sampling at 2 MSPS (18-bit resolution). It can be seen in Figure 1 one of the used modules.

2.1 – Data Processing System Introduction

The last computer bus standard that is being implemented in many international experiments, such as JET and ITER, is the Advanced Telecommunications Computing Architecture (ATCA). A photo of the used ATCA crate is shown in Figure 4. To shorten the data processing time, Field Programmable Gate Array (FPGA) are usually utilized (in Figure 5 is displayed a FPGA). To program the FPGAs is used a HDL (Hardware Description Language) such as VHDL or Verilog, the Firmware which has been used in this work was written in Verilog.
2.2 – Data Processing on the FPGA

On the figure below is shown the block diagram of the first used FPGA logic architecture. This architecture was used as basis for other architectures developed during the tests for this thesis.

![Block Diagram](image)

The data of the ADCs (2 MSPS) is deserialized, passes by a Multiplexer to a FIFO and then a PCIe packet is build and sent, in real time, by DMA, to the host memory. The packet payload comprises a 32 bits word time counter, 16 words of 32 bits with the ADCs data and a 32 bits word with status information.

2.3 – Data Processing Algorithm

There are two corrections needed to be done during or after the acquisition to compensate the “Electronics Offset” (EO) and the “Wiring Offset” (WO). These values are characteristic of the modules and the acquisition board.

![Schematic](image)

The WO is an increment done constantly on the integration at each cycle during the acquisition that is not compensated by the EO Offset correction algorithm done before. In Figure 7 is shown a schematic of the influence of EO and WO.

The procedure starts with the initial average calculation during a few seconds (defined by the operator) of the EO (up to one LSB precision) with the modules inputs short-circuited. The EO is the “After Chop Offset” and after being calculated it is stored in FPGA registers and accordingly subtracted from the incoming data of the board in real-time. The WO can be calculated at the first few seconds defined by the operator (Pre-compensated) or at the end of the acquisition (Post-compensated). The “WO” average drift contribution is subtracted for each DMA packet (in software).

3. Experimental development

3.1 - Signal Reconstruction

At the terminals of the digital ADC module it was set a difference of 19.12V with two batteries. The acquisition frequency was 2 MHz and the chopper frequency was 1.95 kHz. The raw data was saved together with the data from each channel it was also saved the chopper phase signal, so that the signal could be reconstruct afterwards (Figure 8). It can be seen that during the chop’s phase transition only two samples need to be ignored, this shows the remarkable fast behavior of the ADC module design.

![Signal Reconstruction](image)
3.2 – Noise acquisition and integration

The procedure through a short-circuit input acquisition starts with the initial average calculation during 10 s of EO. The WO drift is calculated at the first 100s, if the acquisition is Pre-compensated (Figure 9), or at the end of the acquisition, if the acquisition is Post-compensated (Figure 10):

Not all the data during this first project were being stored in Hard Disk File, the data was down sampled to 1:100 to be saved. Bellow, in Figure 11 and Figure 12, are the results of a long acquisition and it can be seen a representation of the parameters that will be mentioned afterwards. In Table 1, Table 2 and Table 3 are resumed the important values of two consecutive acquisitions.

<table>
<thead>
<tr>
<th>Channel 0</th>
<th>Offset EO (LSB)</th>
<th>Average Offset EO (µV)</th>
<th>1000 s drift WO (LSB)</th>
<th>1000 s Average Drift WO (µV/s)</th>
<th>Mean WO (µV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>– a</td>
<td>-627</td>
<td>(-1084±0)×10²</td>
<td>418498734</td>
<td>(3616±2)×10²</td>
<td>36,16</td>
</tr>
<tr>
<td>– b</td>
<td>-627</td>
<td>418033982</td>
<td>418033982</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Channel 1</td>
<td>17</td>
<td>(3025±87)×10⁰</td>
<td>507920227</td>
<td>(4379±12)×10⁰</td>
<td>43,79</td>
</tr>
<tr>
<td>– a</td>
<td>18</td>
<td>505224903</td>
<td>505224903</td>
<td></td>
<td></td>
</tr>
<tr>
<td>– b</td>
<td>-234</td>
<td>(-4046±0)×10⁰</td>
<td>245198484</td>
<td>(2096±24)×10³</td>
<td>20,96</td>
</tr>
<tr>
<td>Channel 2</td>
<td>-234</td>
<td>239787290</td>
<td>239787290</td>
<td></td>
<td></td>
</tr>
<tr>
<td>– a</td>
<td>-467</td>
<td>(-8057±18)×10¹</td>
<td>216196884</td>
<td>(1844±25)×10³</td>
<td>18,44</td>
</tr>
<tr>
<td>– b</td>
<td>-465</td>
<td>210343139</td>
<td>210343139</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1 - Resume of Offset EO and Offset WO values with constant temperature
### Table 2 - Resume of RMS and Deviation values of Post-Compensated Drift

<table>
<thead>
<tr>
<th>Offset</th>
<th>Average value (uV)</th>
<th>Maximum value (uV)</th>
<th>Minimum value (uV)</th>
<th>Standard Deviation (uV)</th>
<th>RMS (uV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Channel 0 – a</td>
<td>-12.87</td>
<td>0.4140</td>
<td>-27.04</td>
<td>7,432</td>
<td>14.86</td>
</tr>
<tr>
<td>Channel 0 – b</td>
<td>0.1200</td>
<td>11.51</td>
<td>-12.03</td>
<td>5.193</td>
<td>5.194</td>
</tr>
<tr>
<td>Channel 1 – a</td>
<td>-26.49</td>
<td>1.994</td>
<td>-46.10</td>
<td>14.31</td>
<td>30.11</td>
</tr>
<tr>
<td>Channel 1 – b</td>
<td>17.44</td>
<td>42.00</td>
<td>-2.663</td>
<td>12.88</td>
<td>21.69</td>
</tr>
<tr>
<td>Channel 2 – a</td>
<td>16.44</td>
<td>30.61</td>
<td>-0.2430</td>
<td>7.250</td>
<td>17.97</td>
</tr>
<tr>
<td>Channel 2 – b</td>
<td>31.19</td>
<td>52.30</td>
<td>-9.320</td>
<td>13.67</td>
<td>34.06</td>
</tr>
<tr>
<td>Channel 3 – a</td>
<td>-15.13</td>
<td>0.6640</td>
<td>-25.94</td>
<td>6.253</td>
<td>16.37</td>
</tr>
<tr>
<td>Channel 3 – b</td>
<td>-15.29</td>
<td>1.789</td>
<td>-24.16</td>
<td>5.733</td>
<td>16.33</td>
</tr>
</tbody>
</table>

### Table 3 - Resume of RMS and Deviation values of Offset with constant temperature

<table>
<thead>
<tr>
<th>Offset</th>
<th>Average value (µV)</th>
<th>Maximum value (µV)</th>
<th>Minimum value (µV)</th>
<th>Standard Deviation (µV)</th>
<th>RMS (µV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Channel 0 – a</td>
<td>-37.17</td>
<td>5360</td>
<td>-6224</td>
<td>852.1</td>
<td>852.9</td>
</tr>
<tr>
<td>Channel 0 – b</td>
<td>-37.29</td>
<td>5187</td>
<td>-5879</td>
<td>852.1</td>
<td>852.9</td>
</tr>
<tr>
<td>Channel 1 – a</td>
<td>-45.37</td>
<td>5014</td>
<td>-4841</td>
<td>895.2</td>
<td>896.4</td>
</tr>
<tr>
<td>Channel 1 – b</td>
<td>-45.14</td>
<td>4841</td>
<td>-4668</td>
<td>841.8</td>
<td>843.0</td>
</tr>
<tr>
<td>Channel 2 – a</td>
<td>-21.77</td>
<td>6052</td>
<td>-5014</td>
<td>895.9</td>
<td>896.1</td>
</tr>
<tr>
<td>Channel 2 – b</td>
<td>-21.69</td>
<td>6397</td>
<td>-6224</td>
<td>914.8</td>
<td>915.0</td>
</tr>
<tr>
<td>Channel 3 – a</td>
<td>-20.70</td>
<td>1020 × 10^1</td>
<td>-6397</td>
<td>901.1</td>
<td>901.3</td>
</tr>
<tr>
<td>Channel 3 – b</td>
<td>-20.42</td>
<td>1003 × 10^1</td>
<td>-6570</td>
<td>899.6</td>
<td>899.8</td>
</tr>
</tbody>
</table>

During the tests in some acquisition the temperature of the modules were changed, by carefully heating the module with a hot air gun until temperatures of ~43ºC. To study the temperature effect on the integral it was only used pre-compensated acquisitions. The electronic noise was influenced by the changes of temperature that were induced, as it can be seen in Figure 13 and Figure 14.

A pulsed plasma during the operation of a tokamak is a shot discharge in which the plasma goes into one direction. An AC Plasma Discharge is a plasma discharge in which the tokamak’s magnetic field generated by the primary is inverted (by inverting the current on the primary), and with this inversion the plasma current is inverted so that the time in the tokamak that we can have plasma current can be much larger.

### 3.3 – Acquisition of signals from ISTTOK’s Mirnov coils

This sub-chapter is about the acquisition of signals coming from 12 Mirnov coils at 2MSPS with digital ADC modules with galvanic isolation developed by IPFN.

A pulsed plasma during the operation of a tokamak is a shot discharge in which the plasma goes into one direction. An AC Plasma Discharge is a plasma discharge in which the tokamak’s magnetic field generated by the primary is inverted (by inverting the current on the primary), and with this inversion the plasma current is inverted so that the time in the tokamak that we can have plasma current can be much larger.

### 3.3.1 – Pulsed Plasma at ISTTOK

Below is shown the results from an acquisition, with the chop frequency equal to 1kHz and a time discharge of 25ms (Figure 16).
One of the integrals from a Mirnov coils (Figure 16) shows that the signal caused by the plasma occurred at second \( \sim 6.2 \) and is displayed in a blue rectangle. The coils are influenced also by the toroidal field, the instants when the field is being generated are limited by the black pointers. This can be explained by the possibility that during the installation of the Mirnov Coils on a line section of ISTTOK it was unintentionally implemented a deviation relatively to this line section (causing the coils to be influenced by the toroidal field).

One of the signals, the signal that comes from the coil in position number 11, is much smaller than the other signals. This fact that the signal from coils number 11 is smaller can be explained by saying that there could be some deviation during the installation so that the axes are not centered with the direction of the path of the plasma column. This coil can also be damaged.

3.3.2 – AC Plasmas at ISTTOK

Below is presented the results of an AC plasma discharge that lasted more than 1s, with 40 semi-cycles without apparent degradation of the plasma parameters (Figure 18). The average time of each discharge is about 28 ms and the total duration is above 1s.

3.4 - Acquisition tests at IPP, Greifswald

The objective was to demonstrate the performance of the ADC digital modules developed by the Instituto de Plasmas e Fusão Nuclear (IPFN) through tests in the Max-Planck-Institut für Plasmaphysik (IPP) at Greifswald, Germany.

3.4.1 – Integration of a capacitor discharge

It was implemented a simple assembly, using coils and a generator (Figure 19 and Figure 20). The improvised coil had 20 loops of copper and a resistance of \( \sim 0.12 \, \Omega \).
By turning on and off a constant voltage from the generator the signal of the integrator should come nearby zero again. The graphics Figure 21 and Figure 22 show good results about this first test.

3.4.2 – Integration several capacitors discharges during a long acquisition

A test during 1000 seconds was done, to see the response of the modules to a long Pre-Compensated Integration of 1000s. A new assembly was made, it was implemented a capacitor of 33mF with the coil of 20 loops and a resistance of 0.12 Ω from the old assembly. The time constant was about 4ms (Figure 23).

The result can be seen below (Figure 24), each spike at module 0212-016X is a capacitor discharge (Figure 25). Module 0212-0208 is shot-circuit
This test was done also to verify if there was a crosstalk between the modules, as it can be seen in Figure 24 there is no relation between peaks from the consecutive modules. The module in position 2 (0212-016X) was connected to the assembly while the module in position 3 (0212-0208) is short-circuited.

On the above figure the module 0512-0144 (blue line) is a different module of the other two modules, the main difference is a capacitor on the first low filter, instead of been a capacitor of 100nF is a capacitor of 100pF. By this result it is suggested that the modules with the 100nF capacitor are more sensible to the temperature.

Figure 26 - Multiplot of all Pre Compensated Drift on acquisition 3a with the integral of the temperature.

By the results the correction factor needed due to the temperature influence could be calculated by:

\[
\frac{\int \text{Signal}}{\int \text{Temperature}} = \frac{1048 \mu \text{V} \cdot \text{s}}{2960 \text{°C} \cdot \text{s}} \quad (2)
\]

\[
\frac{\int \text{Signal}}{\int \text{Temperature}} = 0.3541 \mu \text{V} / \text{°C} \quad (3)
\]

Or

\[
\frac{\int \text{Signal}}{\int \text{Temperature}} = 2.048 \times 10^{-3} \text{LSB} / \text{°C} \quad (4)
\]

IPFN has currently a project with ADC modules that have a temperature sensor with a resolution of 0.25°C. A
resume of the calculated temperature correction factors can be seen in Table 4.

<table>
<thead>
<tr>
<th>Aquisition</th>
<th>Module</th>
<th>Channel</th>
<th>uV/ºC</th>
<th>LSB/ºC</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 a</td>
<td>0212-0194</td>
<td>0</td>
<td>0.3169</td>
<td>1.833×10^{-1}</td>
</tr>
<tr>
<td></td>
<td>0512-011X</td>
<td>1</td>
<td>0.3541</td>
<td>2.048×10^{-1}</td>
</tr>
<tr>
<td></td>
<td>0512-0144</td>
<td>2</td>
<td>0.08243</td>
<td>4.770×10^{-4}</td>
</tr>
<tr>
<td>3 b</td>
<td>0212-0194</td>
<td>0</td>
<td>0.2906</td>
<td>1.681×10^{-3}</td>
</tr>
<tr>
<td></td>
<td>0512-011X</td>
<td>1</td>
<td>0.3610</td>
<td>2.088×10^{-3}</td>
</tr>
<tr>
<td></td>
<td>0512-0144</td>
<td>2</td>
<td>0.1169</td>
<td>6.760×10^{-4}</td>
</tr>
<tr>
<td>4 a</td>
<td>0512-0101</td>
<td>0</td>
<td>0.2318</td>
<td>1.340×10^{-3}</td>
</tr>
<tr>
<td></td>
<td>0512-0012</td>
<td>1</td>
<td>0.1625</td>
<td>9.400×10^{-4}</td>
</tr>
<tr>
<td></td>
<td>0512-0144</td>
<td>2</td>
<td>0.1134</td>
<td>6.560×10^{-4}</td>
</tr>
<tr>
<td>4 b</td>
<td>0512-0101</td>
<td>0</td>
<td>0.1566</td>
<td>9.050×10^{-4}</td>
</tr>
<tr>
<td></td>
<td>0512-0012</td>
<td>1</td>
<td>0.1786</td>
<td>1.033×10^{-3}</td>
</tr>
<tr>
<td></td>
<td>0512-0144</td>
<td>2</td>
<td>0.1090</td>
<td>6.300×10^{-4}</td>
</tr>
</tbody>
</table>

Table 4 - Resume of the calculated temperature correction factors

It can be seen that the temperature correction factors presented in Table 4 are very similar, but not equal. A possible explanation for this is that the conditions that were induced during the acquisition process were not the same. The local where the tests were made was not an isolated area and there were more people working and with the constant opening and closing of doors the temperature of the room could be changed. Another factor that could influence the results is that the ATCA crate has a cooling system and during the heating with the air gun it tries to compensate the elevation of the temperature. The way that the module were heated may not have been the best due to the directing of the heat to the modules might not been the same leading perhaps to a contribution to the small variation of the final integration that was obtained as well.

The results presented in Table 4 and Table 5 suggests that the modules with the 100nF capacitor are more sensible to the temperature variation, once the average correction factor is higher. The tables also show that the deviation of the temperature correction factors for the modules of 100nF is less than for the modules of 100pF. During the analysis of the temperature influence it was seen that the data from the temperature integral is more easily adjustable to the drift curve of the modules with the 100nF capacitor (as it can be seen in Figure 26 and Figure 27), therefore it could be said that the best modules to work with the temperature adjustments would be the modules with the 100nF capacitor.

4.3 – Acquisition of signals from ISTTOK’s Mirnov coils

The plasma current from an AC discharge of 40 semi-cycles that lasted more than one second is represented in Figure 28. It was obtained by adding the signals from the Mirnov coils of a section of ISTTOK and multiplying by a conversion constant. The value of the integral at the end of the discharge is nearly 0, as at the beginning of the discharge, this means that the “integration problem” was well compensated.

In Figure 29 is shown the plasma current from the same shot of Figure 28, designed as shot number 34531, but obtained by the Rogowski coil. Comparing the figures it is seen that there is a higher integral drift at the measurements done by the Rogowski coil. The main difference between the modules is that the modules connected to the Rogowski coil are not digital modules but analog and they do not use the algorithm to clear the signal from magnetic diagnostics described before.

4.4 – Acquisition tests at IPP, Greifswald

Some of the tests performed in Germany had been done previous in Portugal. These tests that were repeated are...
basically the acquisition related to the acquisitions of short-circuited signals and they presented very similar results to the ones obtained before in Chapter 3.1 and 3.2.

It is seen that in Figure 24 after a 1000s acquisition and many capacitor discharges the shown drift due to the “integrator problem” is very low, less than 50 uV*s. This test was done also to verify if there was a crosstalk between the modules, as it can be seen in there is no relation between peaks from the consecutive modules.

The IPP team focused on DAQ in magnetic diagnostics was satisfied with the performance of the modules from IPFN with the tests that were performed.

5. Conclusions and Future Implementation

In this work it was characterized several techniques and algorithms to have a clear signal of a magnetic diagnostic and it is described the performed tests and obtained results. The used modules were galvanic isolated digital modules developed by IPFN with signal chopper mode and a sampling at 2 MSPS (18-bit resolution) and the used data acquisition architecture was the ATCA. Some of the tests were done with signals coming from simple made assemblies, others with signals from tokamak ISTTOK.

To perform the tests it was been done some modifications on previously used firmware in Verilog and drivers in C and the development of software to assistance the operator, a text based user-friendly interface.

A mission took place in the IPP at Greifswald (Germany). Its objective was to demonstrate the performance of ADC digital modules developed by IPFN. The performed tests give the expected results.

There is a temperature dependency factor that influences the integrator drift. One of the possible ways to continue this work is by studying and implementing ways to make real time corrections on the integration based on temperature sampling. There are modules at the end of the development phase at IPFN that have incorporated temperature sensors with a resolution of 0.25°C.

A second visit to the IPP at Greifswald was done in September 2013 to make new tests on the ADC modules with other assemblies, for testing their performance during the acquisitions on a more realistic magnetic field environment.

6. References


