Control of Nuclear Fusion Experiments

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Engineering Physics

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To my Mother
Acknowledgments

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I special thanks to my friends, for all the moments we spent together either having fun, learning physics or both, also for their help in the making of this thesis, mainly in reading and criticising, so that the end result could become better than it would otherwise be.

Last, but certainly not least, I my grateful to Luzia for her patience when I was grumpy and for her gift to keep me on track.
Resumo

Esta tese insere-se na criação de um novo sistema de controlo lento. O sistema tem uma unidade de controlo, onde três nodos estão ligados e a sua informação é arquivada. A arquitectura do software é baseado no mesmo conceito do ITER, usando o framework do EPICS para publicar os dados na rede do ISTTOK. Para o desenvolvimento das GUs foi usado o CSS.

Um dos nodos permite controlar o sistema do gâlio composto por seis sensores de temperatura e quatro válvulas. O segundo nodo recebe os dados de dois sensores de pressão, um monitoriza a pressão dentro da câmara e o outro a pressão entre bombas do sistema de vácuo principal. O terceiro nodo, implementado nesta tese, adquire dados de quatro termopares instalados ao longo da câmara, adquirindo a diferença de temperaturas entre a câmara e o ambiente. Este último nodo foi projetado para obter os dados da carga do banco condensadores, mas devido a alguns problemas, de momento não se encontra em funcionamento. Actualmente, o sistema corre o software base, mas é necessário mais trabalho de forma a ter um sistema que integre todos os elementos de controlo lento. A máquina de estados tem de ser melhorada, precisa de mais feedback e implementação de outputs. É também necessária a implementação da interacção com o sistema de controlo rápido.

Os objectivos desta tese foram atingidos com sucesso, tanto criação de uma unidade de controlo com todo o software necessário instalado de base e a integração de alguns nodos.

Palavras-chave: Fusão, Controlo, Tokamak, Plasmas, ISTTOK
Abstract

This thesis is part of the development of a new slow control system and its nodes. This system is composed of a control unit and three nodes. The system also archives the data acquired by the nodes.

The software’s architecture is based on ITER’s concept, the EPICS framework is used to publish data on ISTTOK’s internal network. The CSS software was used to develop and run the new GUIs.

One of the nodes controls the gallium system, composed of six temperature sensors and four valves. The second node receives data from two pressure gauges, the first monitors the pressure inside ISTTOK’s chamber and the second monitors the pressure between the primary and secondary pumps. The third node, developed in this thesis, acquires data from four thermocouples installed along ISTTOK’s shell, giving the temperature difference between the shell and environment. This last node was projected to also acquire the charge data of ISTTOK’s capacitor bank but due to some problems it is not ready to be use.

At present, the system has the required software running but more work is necessary in order to integrate all elements of the full slow control system. The state machine needs to be improved, in particular with more feedback and the output implementation. It is also necessary to implement the interaction with the fast control system.

Overall, this thesis’s goals were achieve, nominally the creation of a control unit with all the basic software installed and the integration of a few nodes within the system.

Keywords: Fusion, Control, Tokamak, Plasmas, ISTTOK
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Nomenclature

AC       Alternate current
ADC      Analog-to-digital converter
ATCA®    Advanced Telecommunications Computing Architecture
ATX      Advanced Technology eXtended
BEAST    Best Ever Alarm System Toolkit
BEAUTY   Best Ever Archive Toolset, Yet
BOY      Best OPI, Yet
CA       Channel Access
CAC      Channel Access Client
CAS      Channel Access Server
CODAC    Control Data Access and Communication
CSS      Control System Studio
DAC      Digital-to-analog converter
DC       Direct current
DOS      Disk Operating System
EEPROM   Electrically Erasable Programmable Read-Only Memory
EPICS    Enhanced Physics and Industrial Control System
EVPL     Edwards vacuum program language
FPGA     Field-programmable gate array
GUI      Graphical user interface
HDD      Hard disk drive
HMOS     High performance metal oxide semiconductor
ICF      Inertial confinement fusion
IGBT     Insulated gate bipolar transistor
IOC      Input Output Controller
IPFN     Instituto de Plasmas e Fusão Nuclear
IPMC     Intelligent Platform Management Controller
ISTTOK   Instituto Superior Técnico Tokamak
ITER     International Thermonuclear Experimental Reactor
LED      Light emitting diode
LLNL     Lawrence Livermore National Laboratory
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<td>MARTe</td>
<td>Multi-threaded Application Real-Time executor</td>
</tr>
<tr>
<td>MOSFET</td>
<td>Metal oxide semiconductor field effect transistor</td>
</tr>
<tr>
<td>OECD</td>
<td>Organisation for Economic Co-operation and Development</td>
</tr>
<tr>
<td>PCIe</td>
<td>Peripheral Component Interconnect Express</td>
</tr>
<tr>
<td>PV</td>
<td>Process variable</td>
</tr>
<tr>
<td>RAM</td>
<td>Random access memory</td>
</tr>
<tr>
<td>RCP</td>
<td>Rich Client Platform</td>
</tr>
<tr>
<td>RDB</td>
<td>Relational Database</td>
</tr>
<tr>
<td>SNL</td>
<td>State Notation Language</td>
</tr>
<tr>
<td>UART</td>
<td>Universal asynchronous receiver/transmitter</td>
</tr>
<tr>
<td>UHV</td>
<td>Ultra high vacuum</td>
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Chapter 1

Introduction

1.1 Preamble

1.1.1 Thesis Aim

This thesis is part of a larger project to create a new slow control system to replace the system currently in use at the ISTTOK. This project aims to implement a new prototype system, taking special care to overcome some of the limitations of the current system. In specific, this thesis deals with the core framework and some complementary software for the new system. The goal for this prototype is to integrate some peripheral nodes and develop a GUI to display the data gathered by the nodes.

1.1.2 Motivation

Over the last century, humanity has become increasingly dependent on energy for their progress and sustainability, requiring it for most aspects of modern daily life.

In the last 10 years, energy consumption increased by approximately $10^{20} J \approx 2388 \text{Mtoe}$, a higher rate than ever before and is expected to continue to grow due to the increased energy consumption by growing economies, as can be observed in Figure 1.1. The group Organisation for Economic Co-operation and Development or OECD is, in its majority, formed by developed countries which already have a high energy consumption per capita, around $29 \text{GJ/capita}$. This means that, as history demonstrates, the growth in energy consumption it isn’t very high compare to non-OECD countries. It is also expected that the consumption per capita of the growing economies, which today is close to $6.4 \text{GJ/capita}$, will catch up with OECD countries, leading to a high growth in the world energy consumption, as already mentioned.

Considering how we will satisfy the world’s energy demands in the coming years, we are faced with a problematic reality. Existing energy production technologies are limited either in raw fuel, energy production capability or costs and usually have some environmental issues.

The most common sources of energy are fossil fuels and they have limited reserves. Most of those reserves are found in unstable countries or areas like the middle east, contributing for oscillating prices.
Using fossil fuels as an energy source also has a very high environmental impact.

In contrast, alternative energies like solar and wind, do not have a high production rate and are more expensive, despite their lower environmental impact. From the renewable energy sources, the hydro-power is the cheapest and the one with most usage, it is also the one with the highest environmental impact due to the great area that is required to store water. Nevertheless, at present, renewable energy sources are not enough to satisfy the world’s energy needs, as can be observe in Figure 1.1, not even when thermonuclear is accounted for as well. These two technologies together produce almost a fifth of all energy consumed, as can be observed in red in the last plot.

Thermonuclear technology is controversial mostly because of its radioactive by-products and risk of explosion or meltdown that represent a major environmental impact. It also has many costs, its an expensive project to build, even more expensive to demolish and has high costs with the disposal of the by-products. Taking into account all these expenses, the price per MWh is similar to a conventional coal power-plant, with the difference that thermonuclear has a higher production capability.

Several approaches to this problem are being researched, from the improvement to the technology of today to the development of new ways of producing energy. Nuclear fusion technology is one of these new ways, it can help society improve the production capability in a renewable way. In reality, hydrogen, the fuel for nuclear fusion technology, is not renewable but it is one of the most abundant elements in earth and the universe, so in practical terms it is considered renewable.

Figure 1.1: This graphic shows historical energy consumption records up to 2012, showing projections from that date forwards until 2040. Two types of information are shown. The first, in purple, green and blue, shows the overall energy consumption for OECD countries, non-OECD countries and the world, respectively. The second, in yellow and red, shows the energy production for renewable technologies and renewable technology added with thermonuclear technology, respectively. The data is from the U.S. Energy Information Administration [1] and corroborated by the International Energy Agency [2]
1.2 Foundations Of Nuclear Fusion

The basic principle in nuclear fusion is the fusion of two nuclei into one and during this process there is a release or abortion of energy. The first clue to this phenomena was provided by Einstein in 1905 with his famous relation [3] between energy and mass, equation 1.1, derived from his special theory of relativity.

\[
\Delta E = \Delta m c^2
\]  
(1.1)

Only twenty years later, the British chemist Francis William Aston measured precisely the mass of several atoms, in particular hydrogen and helium. Later, this knowledge was used by a British astrophysicist, Sir Arthur Eddington, who speculated that the Sun could shine by converting hydrogen into helium. In this process about 0.7% of the mass would be converted into energy. In 1939, a German physicist, Hans Bethe, proposed a complete theory explaining the generation of fusion energy in stars [4].

At present, the scientific community agrees that the reaction responsible for the energy emitted by a star is the fusion reaction, using hydrogen as a fuel and helium as a by-product. There are several fusion reactions of hydrogen but the one with most interest for the scientific community is the D-T reaction 1.2 since it is the easiest fusion reaction to initiate. This reaction is the one that has the highest \( \Delta m \) and, through the Einstein equation 1.1, is also the one with the highest \( \Delta E \), which has been experimentally verified.

\[
^1D + ^1T \rightarrow ^2He(3.5\text{MeV}) + ^1n(14.1\text{MeV})
\]  
(1.2)

To be able to create this fusion reaction, several conditions must be met. In stars, the gravity force is able to compress the hydrogen to densities and temperatures so high that allows for the creation of a hot plasma and the ignition of a nuclear fusion reaction in a steady state. On earth, the gravity force is not enough to achieve such extreme conditions, otherwise we would not be here.

After world war two, there was an interest in the development of nuclear weapons and nuclear technologies in general.

It took around 10 years to build a machine capable of producing useful results for later devices, it was called the Zero Energy Toroidal Assembly [5]. It was the first large-scale experiment in fusion using magnetic field confinement to substitute the gravitational confinement existent in the stars. Due to its results, the research in fusion took off, which led to a peace conference in 1958 in Geneva that sealed the start of a truly international collaboration, the EURATOM (European Atomic Energy Community). In time, this collaboration led to the International Thermonuclear Experimental Reactor project, also called ITER [6].
1.3 Technologies For Fusion Power

Through the years several confinement strategies for the plasma were studied: gravity confinement existing in stars, inertial confinement and magnetic confinement\([7, 8]\). Theses studies led to several designs, for devices using different geometries and confinement strategies.

Inertial confinement fusion research started in the 1970s, when scientists began experimenting with powerful laser beams to compress and heat hydrogen isotopes to the point of fusion at the Lawrence Livermore National Laboratory \([9]\) (LLNL). This approach to control fusion is called inertial confinement fusion \([10]\) (ICF). In this concept, powerful beams of laser light are focused on a small spherical pellet containing micrograms of deuterium and tritium, causing it to rapidly heat. This process makes the outer layer of the target explode, creating an inward force, a rocket-like implosion, causing compression of the fuel inside the capsule and the formation of a shock wave, which heats the fuel in the very center and results in a self-sustaining burn. The fusion burn propagates outward through the cooler, outer regions of the capsule much more rapidly than the capsule can expand. Instead of magnetic fields, the plasma is confined by the inertia of its own mass, thus the term inertial confinement fusion.

The other type of confinement, magnetic confinement, was the first technique with a working device, the ZETA already mentioned. This approach takes advantage of the fact that the fusion plasma is a fully ionized gas in which the particles exhibit a collective behavior. This gas is dominated by the electric and magnetic effects which are far-reaching, in opposition to the Coulomb collisions, which are short range. Despite the low electron density and high temperature, close to the temperature of the interior of the sun, a plasma is a highly conductive medium, since the Coulomb collisions are rare. This property means that the plasma has high conductivity so protected by DC (direct current) electric fields across it, though the magnetic fields penetrate into a plasma providing a confinement, the magnetic confinement.

The modern device \([11]\) design was projected by Russian scientists. In the 1970s, results from the T4 tokamak were announced, they had the first quasi-stationary thermonuclear fusion reaction. This design is the dominant experimental technique for studying fusion to this day. Figure 1.3 depicts a schematic of a tokamak, the fuel, in the center, is a low density hydrogen plasma which is confined by magnetic fields to a region in such a way that the plasma does not touch the interior walls. Because of the good results with a magnetic field and toroidal geometry, in 1978 the Joint European Torus\([12]\) (JET) project was launched in Europe and came into operation in 1983 with the current world record of 16MW for fusion power \([13]\).

There are other devices based on magnetic field confinement, for example the stellarator \([15]\), in the past they were very popular and recently interest in them has been renewed due to issues with the tokamak design. They use the same principle as the tokamak, the magnetic confinement, however the stellarator design has a coil incorporated along the torus section, in Figure 1.2 this is represented in the coils which are drawn in blue. The tokamak design does not use these coils, instead a current is induced in the plasma that produces this twist of the magnetic field. Although confinement forces are strong, the induced current can cause a disruption of the plasma, damaging the tokamak. The stellarator has other problems, due to the external twist of the magnetic field the plasma loses its azimuthal symmetry,
instead it has a discrete rotational symmetry. With this symmetry, theory and design development are much harder.

1.4 ISTTOK

1.4.1 General Description

ISTTOK is a small tokamak that started operating in 1993 at IST, its parameters can be seen in Table 4.1. This small tokamak [17] gave to Instituto de Plasmas e Fusão Nuclear (IPFN), at the time called Centro de Fusão Nuclear (CFN), the opportunity to test fusion related diagnostic systems. Thus allowing a broader Portuguese participation in International fusion related projects. It is also an attraction pole for physics students in a university environment, providing basic training in fusion and plasmas.

ISTTOK started installation in 1990 with the acquisition of the several parts from TORTUR tokamak: the structure, the vacuum chamber, the copper shell, the transformer (0.22 V.s), the toroidal magnetic field coils (2.8T), the capacitor banks, the RF power supply (1.7 MHz, 300W) and the discharge cleaning system. TORTUR was a tokamak discommissioned by the Association EURATOM/FOM-Rijnhuizen.
Table 1.1: Main parameters of ISTTOK

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tr>
<td>Major radius</td>
<td>46.0 cm</td>
</tr>
<tr>
<td>Copper shell radius</td>
<td>10.5 cm</td>
</tr>
<tr>
<td>Minor radius</td>
<td>8.5 cm</td>
</tr>
<tr>
<td>Toroidal magnetic field</td>
<td>0.5 – 0.6 T</td>
</tr>
<tr>
<td>Plasma current</td>
<td>6 – 11 kA</td>
</tr>
<tr>
<td>Central plasma density</td>
<td>$0.8 - 1.4 \times 10^{19}$ m$^{-3}$</td>
</tr>
<tr>
<td>Electron temperature</td>
<td>&lt; 120 eV</td>
</tr>
<tr>
<td>Transformer flux</td>
<td>0.25 V.s</td>
</tr>
<tr>
<td>Standard discharge duration</td>
<td>30 ms</td>
</tr>
</tbody>
</table>

At IPFN several systems were developed, such as the vacuum and gas injection systems, the power supply for the toroidal magnetic field coils, a new RF source for the pre-ionization of the gas. Several of the diagnostics systems were also developed in house, the magnetic and electric probes, the microwave interferometer and reflectometer, the Thomson scattering and X-ray systems, the visible spectrometer, the $CO_2$ scattering and laser induced fluorescence systems, the heavy ion beam probe[18] and the control and data acquisition system. Since then several updates were made to ISTTOK as well.

In 2003 upgrades were made to the real-time control[19] also called the fast control, it used DSP-based diagnostics. Recently it has been further upgraded to a new system[20] which uses ATCA for the fast control, a brief description is done in Section 2.3, several upgrades had to be made to ensure compatibility with this new control.

In 2008 a system was developed, installed and tested in order to study[21] the interaction of a liquid gallium jet with the ISTTOK edge plasma. This experiment was integrated in the new control system described in Section ??.

In Figure 1.5 is a schematic of ISTTOK’s torus with the place where the ISTTOK’s systems are currently installed. In the next section, Section 1.4.2, there is a brief description of the several systems.

### 1.4.2 Systems Overview

#### 1.4.2.1 Vacuum System

The vacuum system uses two Pirani sensors with a range from $10^0\text{mbar}$ to $10^{-4}\text{mbar}$ and two ion gauges with a range from $10^{-3}\text{mbar}$ to $10^{-8}\text{mbar}$. The last gauges can be damaged if they are used in pressures higher than $10^{-2}\text{mbar}$. With these two types of sensors installed in ISTTOK, it is possible to have a wide range, which includes the pressures required for plasma formation.

There are also two pumps installed in the main chamber, the primary pump, which is a rotary pump capable of pumping 238 l/m, and the secondary, which is a turbomolecular pump with pumping capability of 385 l/m. These two pumps together with the gauges form the primary vacuum system.

There are four auxiliary subsystems to pump the air from the chamber of the X-ray spectroscope, the heavy ion beam and from the reflectometry system.
1.4.2.2 Gas Injection System

The hydrogen injection system has two gas insertion modules composed of a total of four valves, as can be seen in Figure 1.5. The valve closest to the hydrogen tank and before the two gas insertion modules has the purpose of regulating the pressure and maintaining it at $8.7$ psi, this way the other valves do not have an extreme pressure difference, between the one inside the ISTTOK chamber and the one in the tank. The second stage is separated by the two gas insertion modules working in parallel, one module has a pneumatic valve that controls the on/off and a second valve which is an electromagnetic valve that permits the flow's control. This module is used to set the background pressure. The other module has one piezoelectric valve that permits a fine tuning of the flow and is used for real-time control.

1.4.2.3 Power Source System

The ISTTOK power sources have been recently updated [24, 22]. It has four power supplies.
One of the power supplies is for the toroidal field and is based on a 12-phase rectification. It has a current range from 4kA to 8kA, however normally it is used at 6kA to generate a magnetic field of 0.5T at the center of the vacuum chamber. It was designed with technology of 12-phase delta-star rectification, controlled by an 8-bit open-loop thyristor fire angle control. It has a maximum operation time of 3s.

The second power supply is the primary field power supply, which is a 3.4 F capacitor bank, the ELCO, with a voltage of up to 350V and a current range from -300A to 300A. It uses a dsPIC30F2020 micro-controller to control the switching mode of a H-bridge with IGBTs, it also receives a set-point from the fast control system and a time limit for the operation of 1s is programmed into it as a protection measure. This power source is responsible of maintaining the plasma in the chamber, by inducing the magnetic field that generates the plasma current.

The third power source is the vertical field power supply, which has a 60V DC input and has an output range from -450A to 450A. It has the same control system as the primary field power supply, however instead of having the IGBTs it has MOSFET in the H-bridge. The several coils installed along the torus are used with this source to control the plasma’s vertical position.

The fourth and last power source is the horizontal field power supply, which has a 12V DC input and has an output range from -120A to 120A. It has the same control system as the vertical field power supply. There are some coils, contouring a toroidal section, which are used together with this power source by the fast control system to control the plasma’s horizontal position.

1.4.2.4 Gallium System

This set-up is responsible for the creation of a gallium jet towards the plasma edge inside ISTTOK and the gallium collection afterwards. Figure 1.6 depicts a representation of the set-up scheme. Most of the chosen materials are stainless steel 304 or 316 (AISI) to ensure ultra high vacuum (UHV) conditions and they are also stable when in contact with gallium, that is corrosive, up to 250°C. To avoid inflicting structural damage, the gallium has to be heated up and maintained at temperatures above its melting point, 29.8°C, due to its property of volumetric expansion, around 3%, when reaching temperatures below the melting point. For this reason, the temperature of the gallium and all circuit parts is maintained at 75°C during experiment, apart the injector which can reach 80°C. To produce a
jet, a custom made MHD induction pump was installed with a 2.30 mm round shaping nozzle, ensuring a 2.5m/s flow velocity. For storage, a free expansion tank was installed at the bottom.

A cleaning system was designed and installed to separate gallium from its oxide, otherwise the stability of the produced jets could be compromised and/or promoting the occurrence of arcing due to their lower conductivity.

The device is also isolated from the tokamak vessel and other grounds, which is ensured by 3kV ceramic isolators, apart from the injector which is design to follow the plasma potential, avoiding currents in the jet.
1.4.2.5 Diagnostics System

Through the years several diagnostic systems have been installed, substituted or even decommissioned in ISTTOK, the currently installed ones[22] are described in the following paragraphs.

The ISTTOK interferometer sends a wave with a frequency of 100 GHz through the plasma. This wave is received again and with its frequency it is possible to diagnose the plasma density up to a maximum of $1.24 \times 10^{20} \text{m}^{-3}$.

The tomography diagnostic in ISTTOK[25] was designed in house, with three optical arrays of sensors. Each array has a line of 10 photo-diodes and a disposition that allows a full chamber coverage. These sensors have no filter which grant a detection from x-ray to high infra-red. The goal of this system is the plasma position from the emissivity function.

The heavy ion beam[18, 26] (HIB) has an energy of 22 keV and an intensity of 15 $\mu$A. It allows to perform several different diagnosis, the plasma density, the electron temperature, the poloidal magnetic field and the plasma potential profiles with high spatial resolutions. Due to its high temporal resolution it is possible to perform studies of the fluctuations associated to the previously mentioned parameters.

ISTTOK has two spectrometers installed used to perform impurity studies. One is based on the “Mcpherson, model 2501” and has two modes, the first monitors the evolution of several impurities and the other mode the ions’s temperature[27]. The other spectrometer is a “CVI Laser DK480I” imaging spectrograph and due to its optical design is more versatile than the other one. This system requires manual operation.

The main rogowski coil is a wire wrapped in a helical shape and with a near circular shape. This coil is located inside the copper shell and the coil itself is warped along a poloidal section. It measures the total plasma current.

Similar to the rogowsky coil, the sine and cosine probes are also installed, however they have a variable wiring density in the poloidal direction. This feature allows a linearisation of the probe’s integrated signal with respect to the plasma’s vertical position.

There are 12 Mirnov coils installed, each coil has 50 turns with an area of 25mm$^2$, distributed along the internal perimeter of the vacuum chamber. They measure the poloidal field created by the plasma’s current.

The electric probes[28] currently installed were developed in 2011. They are used to characterise the plasma’s poloidal asymmetries and for an indirect measurement of the plasma’s position by measuring the floating potential[29] at the four poloidal angles. There are also several other configurations of electric probes, being the most predominate one the poloidal array and rake probe. They are used in the measurement of geodesic acoustic modes, zonal flows, plasma Mach number, Reynolds stress and plasma fluctuations.

A compact and simple retarding field energy analyzer (RFEA)[30] was installed in 2006. It measures the temperature of ions in the boundary of the plasma, being one of the most reliable diagnostic systems.

The H$_\alpha$ radiation diagnostic system is based on the principle of the hydrogen’s Balmer series. When an electron “orbiting” a hydrogen transits from the n=3 level to n =2, a photon is emitted with a wavelength of 656 nm. The photon is detected with a photo-diode with a band filter centered at the H$_\alpha$ wavelength.
The loop voltage is used to predict the iron core flux saturation along side with two other inputs (the plasma current and primary field PS current).

1.4.2.6 ISTTOK Security

ISTTOK’s security system is composed of several internal norms and rules. IPFN has policies in place to ensure the safety of goods and personnel, that strives to continuously improve.

The safety of personnel is ensured by rules that limit access to control and operational areas, in particular during ISTTOK operation. Operations are signalled by a visual alarm and, at the time of the power discharge, a sound alarm, in order to alert personnel. Furthermore, for operations that require authorized personnel in the operational area, there are well marked dangerous areas to ensure their safety.

The laboratory equipment also has security requirements to ensure its durability and the ISTTOK’s project viability. One such example is the use of fiber optics for communication, between equipments, which ensures galvanic isolation. Other examples include the restriction of the power usage of some equipments, which beyond a certain time limit could lead to equipment damage. The toroidal field power supply has security norms imposed by EDP in order to safeguard personnel and the power distribution network.

1.5 Dissertation Structure

Chapter 2 discusses the currently installed ISTTOK control system. Chapter 3 presents a new IST-TOK slow control system prototype developed in this thesis. Chapter 4 gives detailed information about the several nodes integrated in the developed prototype system. Finally, Chapter 5 exposes the conclusions of this project and proposes future work.
Chapter 2

ISTTOK Control

2.1 Introduction

The control system is a solution that enables us to control and operate all the machinery in very small scales of time and/or operate it for long periods of time, which would otherwise be imposable.

In a tokamak there are several parameters that would be imposable for a human to have direct control over due to their time scales, an example is the plasma's position. On the other hand, a tokamak typically needs to always be at a ultra high vacuum, this means that the control system should always be monitoring the vacuum status.

ISTTOK's control system and data acquisition system were projected [31] to have three main operation modes, Figure 2.1, a mode to start, shut-down and for vacuum maintenance, another one to perform cleaning discharges and a last one to perform the power discharges.

The control system can be separated into several systems working together, the plasma control or fast control, the technical control or slow control, the FireSignal, the Triggers and the data storage handled by the FireSignal. Figure 2.2 represents a diagram of these several systems and the interactions between them.

In general, the slow control system is responsible for the secondary equipment, which in fusion reactors assures safety of the personnel, the energy and fluids storage and transport, the vacuum and cryogenic systems, handling the radioactive by-products and giving the ability of remote control. In ISTTOK, the slow control system controls the vacuum system, the warning alarm, the gas injection and the energy storage and transport.

ISTTOK's fast control system is responsible for the power discharge, where the plasma is created and stabilised. Parameters like the plasma's position and the plasma confinement are in the care of this system as well.

The other systems are used to coordinate the interaction between the slow control system, fast control system and the data storage system, which can be seen in Figure 2.2, where the two control systems do not communicate with each other directly.
2.2 Slow Control System

The slow control system, or technical control system, currently installed in ISTTOK [32] uses a vacuum control system, the EDWARDS 2032, that has proven its reliability as it has been working since
Figure 2.3: Schematic of all the connections between the slow control unit, EDWARDS 2032 and its peripheral nodes, from [33].

1991 without any major problems. Nevertheless it is an old programmable system with a proprietary language, Edwards Vacuum Program Language (EVPL), has no support due to its age, which could be a problem if this unit breaks down since there is a lack of a replacement.

This vacuum control unit is an autonomous unit and uses the EVPL, as mentioned earlier, which is compiled with a DOS program. Subsequently the binary is sent to the EDWARDS. The vacuum unit is equipped with an Intel® 8085 8-bit HMOS microprocessor with 6.36KBytes of RAM memory, an EEPROM20 with 8.19KBytes and a serial port.

The vacuum control unit was designed to process automation of vacuum systems. To achieve this purpose, the vacuum pumps and pressure probes are connected to it. It is also possible to connect it to electro-pneumatic equipment. At present, this unit is responsible for all the slow control, Figure 2.3 depicts the connection scheme for this supervisor/control unit. Currently this central unit does not have room for new nodes. The communication with the fast control system is limited, this system only receives two input signals, Figure 2.2, and this is a reflection of the unit's limitations.

The state machine for ISTTOK's operation, Figure 2.1, is not entirely programmed in this control unit. Some of the operations are manual. Figure 2.4 represents the state machine that is programmed in the slow control unit.

The first state, the vacuum stage, can be sub-divided in three sub-stages. Starting with the offline sub-stage, in this stage, the machine is totally turned off and it is used when it is scheduled that ISTTOK will be stopped for a long period or when it is necessary to open ISTTOK. In this sub-stage the chamber is at atmospheric pressure. Another sub-stage is the primary vacuum sub-stage. This stage is used
as an intermediary sub-stage for the other two, because some systems require some conditions to be met in order to turn on, an example is the turbomolecular pump. In this sub-stage the ISTTOK chamber can achieve a pressure as low as $10^{-2}$ mbar. The last sub-stage is the high vacuum sub-stage, which is designed to be used 24/7. This means that ISTTOK is maintained at high vacuum, at $10^{-7}$ mbar, at all times and has to be completely autonomous. This state is named “PROCESS” in slow control. All these sub-stages are done automatically by the slow control unit. In this way, ISTTOK is always ready to be used without requiring a long period for preparation, which would be necessary if the ISTTOK were in the off-line sub-stage. The main system used to maintain the apparatus in this state is the vacuum system described in Section 1.4.2.1.

The goal of the cleaning discharge state is to clean the primary chamber from impurities that typically get embedded in the shell during higher pressures. This discharge is based on a glow discharge principle, which uses an AC discharge to create a low temperature plasma with a frequency of 50Hz. Before changing the machine state, the operator has to manually connect, through a relay selector, the primary inductor to the grid, for an AC discharge. The operator must also turn ON a multimeter used to measure the shell’s temperature and place the controller of the needle valve in manual mode. Only af-
After this preparation may the operator send an order to the control unit by pressing the "E" key. This order changes the state of the control unit from "PROCESS" to "MANUAL". After this process, the machine is now in the cleaning discharge state and the sub-stage is the standby state. In this sub-stage the operator verifies the status of the rest of the systems. The next sub-stage, the glow discharge, is responsible for the cleaning process of the shell, which is heated by the combined effect of the created plasma, that is not well confined, and a heating blanket. To enter this stage, the operator sends several commands to the control unit to initialize the necessary systems. First the operator must give a command, "Q", to start the gas injection system, followed by the command, "S", to turn ON the ionization system. The third command, "M", is to turn ON the heating blanket. The last two commands are related to the source of to toroidal field source, the first one, "O", connects the source to system and last one, "N", turns it ON. The operator controls the pressure during the discharge, maintaining it at ≈1mBar, and when the thermocouple multimeter reaches the value of 3.9mV, the operator turns off all systems by sending the "D" command to the control unit. Upon receiving this command, the control unit changes its state back to "PROCESS".

In the power discharge stage, it is necessary to use the fast control system that is described in the next section, Section 2.3. It is in this state that the plasma with typically the most scientific interest is created. To begin a power discharge, the operator must give the "B" command to the slow control unit, which causes it to transit to the the state "WAIT-VME". In parallel, the operator configures the fast control using a remote configuration layout. After the fast control system acknowledges and configures all its systems according to the operator's instructions, it sends a signal to the slow control system through the FireSignal and the VME triggers, Figure 2.2. Then the slow control unit changes the internal state to "L_IF_SC.". In this state the ELCO is charged and the injection system is turned on. Next the slow control system sends a signal to the FireSignal, using the optical module, and then changes its internal state to "SHOT". In this state, the charge of the ELCO is stopped and the plasma control is done by the fast system. The slow control unit waits seventeen seconds to switch to the state "PAUSE". The purpose of this state is to ensure that all equipment is ready to repeat another shot if necessary. The ELCO is discharged to 0V and the injection system is turned off. The coils of the toroidal field, that use the 12-phase power source, need to be cooled down for three minutes, since they typically have a current of 6kA travelling through them. This imposes a minimum wait time between discharges. When this delay is over, the slow control unit makes a transition to the state "WAIT-VME".

2.3 Plasma Control System

The installed control system uses the ATCA® technology [20, 22]. The control unit was developed recently in the laboratory and is composed of a ATCA® board [34] capable of real-time control and two ATCA® acquisition boards.

Each acquisition board has 32 differential inputs, with galvanic isolation, linked to 18-bit resolution ADCs operating at 2 Msamples/s; storage capability; a rear transition module with a trigger/clock input; and eight DACs. They also have a Virtex XC4VFX60 FPGA responsible for the control of the data.
acquisition, processing and transfer. The FPGA is also responsible for the interaction with the ATCA® controllers, the connection with the control board and RTM board and the configuration and synchronization of components. The ATCA® control board includes a standard ATX Asustek motherboard with an Intel® Core™ 2 Quad Processor Q8200 chip with a 64-bit instruction set and a clock speed of 2.33 GHz. The installed operating system is a custom version of Gentoo Linux [35] with the MARTe framework [36, 37]. This motherboard is mounted on top of a support board that attaches to the ATCA® crate. The support board grants access to the required interfaces for: the peripheral Component Interconnect Express (PCIe) connection, the hard disk drive (HDD), the Intelligent Platform Management Controller (IPMC) to communicate with the ATCA® shelf manager, the adequate voltage supply, the on/off for the motherboard, the front panel LEDs and everything else related with the PCI Industrial Computer Manufacturers Group (PICMG) 3.x protocol implementation.

Figure 2.7 depicts this control system and its peripheral nodes. Linked to the ATCA® control board there is also a PCIe card that provides four serial ports. The card is connected to three power sources, the primary field power source, the vertical field power source and the horizontal field power source. The two ATCA® acquisition boards receive data from a subset of the ISTTOK diagnostics, such as the main rogowski coil, the Mirnov probes, the electric probes, the tomography system, the sine probe, the cosine probe, the h-alpha bolometer, the interferometer and the loop voltage. This data is streamed at 40 Mbit/s to the FPGA were it is filtered with a finite impulse response filter with a cut-off frequency of 10kHz. Then the data is converted to a frequency of the control cycle application, about 20kHz and sent to the control board by the PCIe protocol.

The fast control system gives the operator several options to configure it. This is done through two objects named the Discharge Configuration and the Advanced Configuration. These objects are accessed remotely and are available in the ISTTOK’s internal network with a browser. An example of the available options is the type of operation, possible choices are, a pre-programmed current waveform,
a proportional–integral–derivative (PID) controller that uses the plasma position or plasma current and auto-PID.

The control cycle, Figure 2.6, has a duration of 100\(\mu\)s. This control is carried out during a power discharge. The power discharge can be divided into two groups, a DC power discharge and an AC power discharge. The DC discharge time is limited by the hysteresis loop of the iron core and is about 66ms. In ISTTOK, to overcome this limitation, the AC power discharge was implemented. In this discharge there is an inversion of the current going through the iron core. This means that there is an inversion of the plasma current. To achieve this inversion, the time window paradigm was implemented in the fast control system. In this paradigm, the actuator’s control type can change in each time slice. There are five sets of programmed time windows, two for the positive cycle and two for negative one, although the operator only needs to specify two of them. The discharge begins with the time window for the “breakdown waveforms” and has the goal of achieving plasma breakdown. The time window is then switched to the “positive current time windows”. When the iron core is approaching saturation, another time window transition, to the “inversion to negative current”, is triggered. When the plasma current is in the opposite direction, the control is handed to the “negative current time windows” and, once again, when the iron core is approaching saturation, a transition is triggered to the time window “inversion to positive current”. These last four time windows work in loop until the end of the discharge. The actuators used are the primary field source, the vertical position source, the horizontal position source and the module of gas injection.
2.4 Middleware

The middleware is the FireSignal [39] and the system of triggers [40]. Figure 2.2 represents its integration with the two control systems.

The FireSignal was designed to control and operate physics experiments in a full modular concept and avoids dependency on a particular technology. Each hardware client uses the plug-and-play philosophy to connect to the FireSignal central server, programmed in Java. It is this central unit of middleware that is responsible for managing all of the commands, for the system configuration, access to the database and data broadcast. For the users, there is a graphical user interface (GUI) to access the data in a cooperative environment.

The interaction with the slow control is very limited and at the moment only two signals are exchange, those already mentioned in Section 2.2 and there is no data record from this control unit. The slow control unit receives a trigger signal from the FireSignal, this signal is sent to it through a trigger signal that was developed to synchronize several systems. Currently this is the only input sent to the control unit.

However, for the fast control system, a driver was developed and installed in the three boards so that the FireSignal can access all the data stored in the fast control system at the end of each discharge. From the control board, the FireSignal stores the raw data from diagnostics, the observed plasma parameters, the values sent to the actuators and some auxiliary data, internal control variables for debugging purposes. From the acquisition board, the FireSignal stores the data acquired from the diagnostic tools connected to each board.

2.5 ISTTOK’s Slow Control Future

2.5.1 System Limitations

The current slow control system is outdated. As mentioned previously, the programming language, EVPL, lacks modern capabilities of high level programming languages. The interaction with the operator is done through a terminal, also lacking a GUI.

The interaction with the FireSignal is minimal and is based on a triggering system during the power discharge. There is no storage of the data acquired in this unit, an example is the background pressure data during the vacuum stage or the cleaning discharge state.

The control unit’s expandability is limited to its control bus that is fully occupied and its processing capability limits the instructions’ complexity. As mentioned it has an Intel® 8085 8-bit HMOS microprocessor with 6.36KBytes of RAM memory, which compared to the today’s systems is extremely outdated.

The slow control unit is also based on a centralised philosophy. This means that if it is required an intervention to this unit the all its sub-systems have to stop consequent ISTTOK has to stop.

Finally, this unit was discontinued by its manufacturer, implying that in the event of a malfunction, it would not be possible to replace, and even simple repairs can be challenging.
Due to these several limitations, ISTTOK requires a new control system that can overcome all these limitations and that ensures support and simplifies compatibility problems in the development of new systems for other tokamaks.

2.5.2 ITER Approach

The ITER project is being developed by several countries that together represent more than half the world. Consequently, integration represents a major challenge to the project. The core system is being developed by the host, the ITER Organization, and must be prepared to support interfaces to control the local systems created by the member states.

A global architecture [41] was developed, with standards, protocols and methodology to have better process integration and automated operation from a central location. The architecture developed for the control system is called Control, Data Access and Communication or CODAC [42, 43] and will provide continuous supervision, data monitoring, visualization, storage and handling, alarm handling, error logging, plant’s system automation, operation state management and schedule management, automated pulse execution and real-time plasma feedback control functions for the overall ITER operation.

The chosen solution to this problem was the use of a common software framework, interface and GUI which allows all device systems to be independent of the hardware where they are running. The used framework is called EPICS [44] and uses for communication middleware the channel access (CA). Control System Studio (CSS) was opted as the central GUI development framework.

This framework also has integration with the MARTe framework [45], which means a deeper integration would be possible between the fast control system and the slow control.

Opting for using these technologies also brings ISTTOK nearer to the ITER fusion community, with its support and increasing the compatibility between ISTTOK’s system and ITER’s system.
Chapter 3

New Slow Control System

3.1 Introduction

The most important requirements for the new slow control system are reliability, resilience, external connectivity, modularity, compatibility with the installed systems and easy programmability. On the downside the installed system is old and its core is a bought system whose production and assistance have discontinued.

A new system is required to overcome the downsides of the current system, it should reunite all the necessary traits already described. Figure 3.1 represents a schematic of a system running experimental physics and industrial control system (EPICS) and other tools, inside the blue boxes are future possibilities for expansion. The installed prototype control unit, and currently running, has three peripheral nodes, depicted in the figure, these are the gallium node, connected to the port ttyS0, the temperature sensors node, connected to ttyS2, and the pressure sensors node, connected to ttyS3. These nodes are using the RS-232 protocol and are further explained in Chapter 4. This chapter is focused on the control unit and the operator terminal.

3.2 System Structure

Returning to Figure 3.1, channel access (CA) is the protocol that all communication is based on. This protocol works in a higher layer, with the TCP/IP and UDP protocols behind. It uses the client/server and publish/subscribe techniques, which allow sharing of information between several hundred computers. Consequently, the system has an almost infinite capacity for expansion, at least for the ISTTOK’s needs in this area.

The EPICS framework implements and uses the CA protocol to publish in the ISTTOK’s internal network the process values (PV) in the case of the server. The PV are variables in this framework and they are composed of several fields, each field with a particular information about the PV. Two examples of these fields are a value field and a unit field. This framework is also prepared to have software modules and extensions. Typically the modules give EPICS new capabilities, like asynchronous communication,
and the extensions are extensions to other software, such as the extension to MATLAB or LabVIEW.

The new slow control unit, that works as a server in this framework, has four input output controllers (IOCs). The IOCs are the interfaces of EPICS, which holds and runs a database of records representing either devices or aspects of the controlled devices. There is one IOC that has information of the state machine and the other three hold the information of one node. Lastly, there is a data archiver, running in the server, with the job of saving the values of the PVs. The saving of the parameters is defined in the PV fields, in particular the time interval between savings and based on variation of the PV value.

Figure 3.2 represents the directory tree of the developed solution. By default, when compiling the source code the application is installed in the same top directory. This behaviour can be changed as well as the directory paths of EPICS and its modules which are defined in the CONFIG_SITE and RELEASE files located in the configure directory. All the source code files are located inside the ISTTOKApp directory and are divided into two folders. The Db folder contains all the code in EPICS, using the EPICS framework language with the extension *.db. It is in these files, the *.db, that the PVs and their fields are defined. The other folder, the src, contains the application source code written in cpp and
is used to create functions and/or operations that are somehow linked to the application but are done in lower layer in the EPICS shell. The iocISTOK directory contains the file st.cmd. This file has the necessary definitions of the db files for the drivers and when executing it calls the EPICS shell running application, located in the Top folder, in this case the ISTTOKApp. The rest of the folders are generated automatically when compiling.

The control unit has three nodes plugged-in: the vacuum node to the serial port ttyS3, described in Section 4.2.1, the temperature node to the serial port ttyS2, described in Section 4.2.2 and the capacitor bank reading described in Section 4.2.3 and a third node, the gallium node, to the serial port ttyS0, described in Section 4.2.4.

The operator terminal also has an instance of EPICS running to access to the PV, though this instance is integrated in the graphical suite, the Control System Studio (CSS). CSS is a collection of tools: Alarm handler, archive engine and operator interface (OPI). CSS is implemented in Java, using the Eclipse software framework, specifically the Rich Client Platform (RCP). With the use of the Java programming language and runtime environment it is possible to create software capable of running on any operating system. Due to Eclipse RCP framework used to build CSS, CSS is prepared to integrate plug-ins that could otherwise be a stand-alone control system application collection of Eclipse Plug-ins. In CSS, what turns into a plug-in, for example the Data Browser, that displays strip-chart type plots of Process Variable values over time. Though some of the CSS plug-ins are in reality individual applications, the Alarm Server and the Archive Engine are examples of stand-alone RCP applications that use essential CSS library code, but they are nevertheless executed as individual application instances.

### 3.3 Serial Communication

The hardware used as peripheral node in this the system was the IPFN dsPIC board version 2 connected via serial cable using RS-232 protocol.

To implement the serial communication in EPICS it is necessary to install the Asynchronous Driver Support (asynDriver) module. This module has the purpose of facilitating the interface for device specific code in low level communication drivers, permitting a standardization in implementation of interfaces, without the need of development of an interface for every asynchronous communication protocol. In
Table 3.1: Codes of the developed message protocol exchanged between the control unit and the peripheral nodes

<table>
<thead>
<tr>
<th>Message code</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>PR</td>
<td>The following value is a pressure</td>
</tr>
<tr>
<td>PRD</td>
<td>The following value is a wave period</td>
</tr>
<tr>
<td>TE</td>
<td>The following value is a temperature</td>
</tr>
<tr>
<td>UP</td>
<td>The following value is the running time of the device</td>
</tr>
<tr>
<td>VL</td>
<td>The following value indicates a valve state</td>
</tr>
</tbody>
</table>

In this project, the asynDriver was used in the development of the device driver for the IPFN dsPIC board version 2.

The configuration of the serial port is done with the st.cmd file, it is also created a link between port (ttyS0 as example), the driver itself and db file. In this case, the PVs declared in the db file need to have two fields, one is the DTYP field, where it is specified the device type, and the other field can be the input field (INP) or the output field (OUT), which hold information of a variable that will be linked by the asynDriver.

The source code for the protocol, using the asynDriver interface, is located inside the src folder, Figure 3.2 for reference. In this folder there are two files, the serialPicAPDriver.h and serialPicAPDriver.cpp. The first has the declaration of the variable that should be linked to the db file via st.cmd. The second configures the Linux device with the parameters given in the st.cmd file.

This second file also holds the code for message handling exchange with the node. When a message is received, all the information that it holds is identified and separated in variables that will update the linked PV of the db file. The received message has the following structure, "Code_Number Code_Number (... UP_Number CRC)"; Table 3.1 discriminates all codes currently implemented.

In the developed protocol, there is no request for information, instead the node is periodically sending a status message. If the message is not read properly an error message is generated for the operator. A verification is done using information of the UP field that reveals if the node is sending the status messages regularly.

3.4 State Machine

To implement a state machine in EPICS, it is necessary to install another module, the State Notation Language (SNL), also known as the Sequencer, which consists of the SNL compiler and runtime system. This is a set of tools that provides a human readable programming language and is smoothly integrated with EPICS base, depending and building upon it.

With SNL the created program is structured as a set of finite state machines, called state sets. These states are defined in the IsttokSeqExec.stt, IsttokSequenceExecution.stt and PulseSequenceExecution.stt files locate in the src folder, Figure 3.2 for reference. In turn, the finite states are defined under conditions (when). Once one of the conditions is fulfilled, the state changes to another state, respectively executing the programmed actions once the transition is triggered. Several states were
created, Figure 3.3, this is a conceptual state machine working as a prototype. All the transitions in this state machine have as origin an order given by a user.

The binding between the SNL variables and the PVs is done in the stt file itself, in such a way that the value of SNL variable gets continuously updated whenever the value of the associated PV changes, Table A.4. These variables can be used for the state transition conditions and the runtime system takes care that the conditions are evaluated when, and only when, changes to the associated PV occur.

During transitions it can be necessary to explicitly update the SNL value. This is done using a built-in function, pvGet. In the same way, it is possible to update a PV from the SNL value, using the function pvPut.

Another important feature resides in the compiler, it manages all the mechanism details of PV subscriptions behind the scenes, simplifying the state machine program. It also takes care of maintaining the variables’ integrity, even in the presence of multiple concurrent state sets inside a single program (at least in Safe Mode). Programming in SNL is free of deadlocks, a common problem in multiprocessing systems, parallel computing and distributed systems, that happens when process/thread is waiting for resource held by another process/thread, that in turn is waiting for another resource. SNL is design to be compatible with C and as most of the SNL syntax and semantics are directly inherited from C, meaning that when programming with SNL it is possible to call C procedures.

3.5 Archiver

The archive system is currently installed in the new slow control unit, however in the future this database will migrate to the ISTTOK database. The chosen archive system is one of the most popular for EPICS, BEAUTY. This system is part of the built-in tools in CSS, and was developed as a replacement for the Channel Archiver.

The BEAUTY system records data from the front-end computer through the CA and stores the data in a MySQL database. Figure 3.4 represents a flow schematic of the archive system. A user was created in
the database with read/write permissions to be used by the ArchiveEngine otherwise the ArchiveEngine could not access the database. This engine also supports other types of Relational Databases (RDB), like Oracle or PostgreSQL.

The archive system has an xml configuration file where the PV that should be stored is defined. The PVs are being saved every 30s or when the last saved value has a high difference from the one published in CA from the server. This difference is defined in a PV field called ADEL.

The databrowser is the CSS viewer for database and the configuration only needs the user credentials to access the database, this user typically only has permission to read.

3.6 Alarm Handler

The tool used for this system is the Best Ever Alarm System Toolkit or BEAST. It is based on the original EPICS alarm handler, ALH, combined with new ideas from the CSS project.

Process Variables are used as Alarm triggers. The way this works is that when the PVs are outside a certain predetermined range of values, a minor severity occurrence is triggered. If these values go beyond a broader range of predetermined values a major severity occurrence is triggered.

These limits are defined in the IOCs by the user through the HIHI, LOLO fields and the HIGH, LOW fields. The first two fields define the major severity range, and the last two the minor severity range.

The Alarm Handler, besides detecting PVs and triggering the alarm, also manages this alarm, i.e. it keeps the alarm on, until a user acknowledgement, or the return of the values to the appropriate ranges, and can generate a system occurrence Log message. In the control unit prototype an alarm server is
installed, as depicted in Figure 3.2, that is responsible for the management of alarms.

3.7 The Graphical User Interface

Control System Studio is a collection of tools: Alarm handler, archive engine, as well as operator interface (OPI) used to in the development of the Graphical User Interface (GUI). To install it is a simple operation of zip extraction and copy to the desire folder, when running it the user will asked for the working directory, this directory holds the developed OPIs, scrips and all the files necessary to run the GUI, in Figure 3.5 is represented the directory tree.

This program is a suite of several tools, as already stated, it also has several layers running. One of the layers is the Data Access Layer (DAL), it is this layer that accesses the CA and manages all the publishing and subscribing, simplifying the user’s and developer’s tasks. The DAL can also be used to access other protocols, different from CA, however this capacity was not explored.

Several OPIs were created, located inside the OPI folder. One of the OPIs is design to control the gallium experiment, Figure B.2, the details for this node are describe in Section 4.2.4 and Section 1.4.2.4. This GUI allows the control of four valves and the monitoring six temperatures sensors. Each valve has two PV, one to send the operator commands and another PV to holds the last known state sent by the node. Each sensors has a PV that holds the last known value, the operator can find in the GUI a plot. There was also create an OPI with experiment schematic holding the information of valve state and temperatures. An OPI to substitute the pressure monitor was created, it has the information acquire from one of the nodes connected to some pressure sensors, Figure B.4. A third OPI, Figure B.3, to be used by the operator to control the state machine and has an information resume of all important information this last one is limit to information acquire at presently. And finally one last OPI, Figure B.1, was created to work as a menu to navigate through the OPIs. All the OPIs were developed using the BOY toolkit.

The archiving process already discussed is installed and implemented in the server. But the BEAUTY toolkit has another feature, the data browser a built-in GUI that permits access to the ISTTOK archive located in the EPICS server, Figure B.5.
3.8 Integrated Peripheral Nodes

As is depicted in Figure 3.2, the developed control unit has three peripheral nodes, the vacuum node, the temperature node and the Gallium node. These nodes use the communication protocol described in Section 3.3, and detailed information on the peripheral nodes can be found in Chapter 4.

The vacuum, temperature and Gallium nodes are connected to the IOC server through ports ttyS0, ttyS2 and ttyS3 accordingly.
Chapter 4

Integrated Peripheral Nodes

4.1 Hardware Platform Description

The control unit running EPICS and working as a supervisor/central node, is an Intel® Atom™ CPU 330 @ 1.60 GHz, Dual Core, with 1 Gbyte of random access memory (RAM), 4 Serial Ports and two Ethernet ports. It is connected to an internal ISTTOK private network and to a peripheral system composed of 3 IPFN dsPIC boards [46] by RS-323 protocol.

These 3 peripheral nodes have an eurocard format with several interfaces, in particular the RS-485 and RS-323 ones as well as a DIN96 eurocard connector. The input power supply is an unregulated DC 5 V to 35 V with a power supply regulator allowing other output of 5 V at a maximum of 1 A. The micro controller is a Microchip dsPIC30F4013 with several 10bit ADCs that can access 4 multiplexed sample and holds. The second version of this board has a dsPIC node with a power h-bridge and Microchip dsPIC30F4011 support. The third version is similar to the second version although its dimensions have been reduced to 100x100mm. These two micro controllers can be programmed in C using MPLAB with
its compiler, and the Pickit 3 to program the device.

This board was chosen for its versatility, availability and low cost and fulfills all the integrated nodes’ requirements.

4.2 Peripheral Hardware

4.2.1 Pressure Sensors

Mounted to ISTTOK there are two Pfeiffer MPT100 pressure sensors, Figure 4.2, which have a range of $5 \times 10^{-9}$ mBar to 1000 mBar. These sensors allow the software and the operator to monitorize the pressure in ISTTOK’s chamber, and between the two vacuum pumps.

![Figure 4.2: Pressure sensor MPT100 installed between the primary and the secondary vacuum pump](image)

The previous system was reading from the chamber. Though the firmware was not prepared to read from two sensors and to communicate with EPICS. Thus, it was necessary to modify the firmware of the micro controller to comply with this two requirements.

With the new firmware, the micro controller acts as a master when communicating with the two sensors, the slaves, through the RS-485 protocol, Figure 4.3. The ISTTOK’s chamber sensor has the address 001 and the one between the vacuum pumps has the address 002. Every 500 ms the micro controller asks for values, first to the 001 sensor, then waits for the new value. After receiving the value

![Figure 4.3: The two MPT100 sensors are connected to the micro controller by a multi-drop topology](image)
from the 001 sensor, it asks the 002 sensor for its value and again waits for a new value. In this way, the risk of collisions is avoided.

After all data has been processed, it is automatically sent to EPICS with the protocol described in Section 3.3. A list of all PV related with this node can be found in Table A.1.

4.2.2 Temperature Sensors

4.2.2.1 Introduction

These sensors give the temperature information of the ISTTOK’s shell to the operator. This information is important to detect anomalous temperatures during ISTTOK’s regular operation, however it is even more relevant during a cleaning discharge since the shell heats up the most during this type of discharge. ISTTOK has, at least, 4 working type K thermocouples. There are more thermocouples installed, even though they are not working at the present time, the system is prepared to handle their possible use. Currently, only one is being monitored with a multimeter and its data is not being stored.

The developed board aims to improve this monitorization and connects the thermocouples to the IPFN dsPIC board, Figure 4.4, which is responsible for the signal digitalization and data transmission to EPICS. Every 500 ms the micro controller toggles between reading the ADC or sending the stored data to EPICS.

![Figure 4.4: Connection schematic of the developed board](image)

4.2.2.2 System Description

The preferred choice for the dimensions of the board was the eurocard format. However, since this would be a waste of material, a 100x100mm board was chosen instead, coinciding with the last version of the IPFN dsPIC board.

The board requires a power source capable of supplying 5 V at 4 mA, preferably a regulated supply. The IPFN dsPIC board’s power supply was used since it met all the requirements and there was no need to design a specific integrated power supply in the board.

The board has 8 differential input channels, it is entirely analogue and prepares the thermocouple’s signal to be digitalized by the IPFN dsPIC board, which would otherwise be impossible due to the
thermocouple’s low voltage output. Since the ADC of the micro controller requires the use of a 5k Ω resistor connected to its input, this resistor was integrated in the design.

The board’s output varies from 0.4 V to 3.5 V. The inferior limit is given by the offset voltage of the operational amplifier (Op. Amp.). This is a known disadvantage of this design and in this case it is amplified by the gain stage, that increases this offset even more, Figure 4.5.

![Circuit schematic for one input signal](image)

Figure 4.5: Circuit schematic for one input signal

This first gain stage is the highest gain stage ($\frac{V_{in}}{V_{out}} = 300$) and has to be the highest gain due to the characteristics of the signal (low voltage and low current), otherwise the Op. Amp. would not pick up the signal. The upper limit is given by the LM358, and it can be improved by using a better Op. Amp. or by using a higher supply voltage. The second stage has a low gain($\frac{V_{in}}{V_{out}} = 2$) and a filter with a cutoff frequency of 1.6Hz.

As for the installed thermocouples’ input signals, they are low voltage and low current, as mentioned before, and have a slow slope so a low cut off frequency filter does not interfere with the signal evolution. These thermocouples at ISTTOK usually have an output range of 0 mV to 4 mV, even though they are capable of a wider range.

The overall expected output of this system goes from the lower limit of the board’s output to the maximum expected thermocouple value times the board gain, reaching up to 2.7 V. Since both the board’s and the thermocouple’s upper limits go above this, this system can also monitor anomalous or erroneous measurements, so that any malfunction can be detected.

4.2.2.3 Assembly

The development of this board was done in two stages. The first is the prototype stage, where two board designs were tested in several different approaches and the chosen design is depicted in Figure 4.5.

A different design used instrumentation amplifiers and had the advantage of handling better the bias current, which is a problem in the chosen one. However it also has two significant drawbacks, it is
Figure 4.6: Silkscreen of the thermocouple board. The red net marks the supply net (VCC), light blue marks the ground net and the regular net is identified in blue.

more expensive and the gain in the first stage must be very precise because it could easily saturate the amplifier. The chosen design was additionally tested with several gains in the prototype stage.

The second stage was the PCB design and production stage and for this purpose Orcad suit was used. In Figure 4.6 it is depicted the bottom layer’s representation.

This board has two layers, mainly because of routing issues in the LM358 supply net, since it crossed over other paths when using only one layer. Due to its higher precision and its broader choice of values, surface-mounted resistors were used.

Finally, the DB25 connector was used because the DB9 connector lacks the appropriate number of pins and the DB15 connector was not available in the laboratory. DB25 has the required number of pins and there are plenty of these connectors in the laboratory.

It takes 5 hours of labour to produce this board, with a cost of approximately €13. Table D.1 has detailed information about the components used and a full board schematic can be found in Figure D.1.

4.2.2.4 Testing the board

Two tests were done with the chosen board. The first test is a safeguard protocol and was done to detect any malfunction in the board without the risk of damaging the thermocouple. The second one audits that everything is working properly.
Figure 4.7: In figure (a) a single acquisition is represented in purple and in green is an average of the 1024 acquisitions. The data represents a full clean discharge. Where we notice a rise in the data is for the part of the discharge in which the shell temperature rises in comparison to the environment temperature. Where it decreases, it shows the cooling curve, the rectangle indicates the area of the graph with the highest errors. Figure (b) represents only the cooling process fitted to the data. The fit properties are shown in Table 4.2, note the plotted fit is shifted in the time axis by 1360s.

- The first test consists of:
  1. Plug the board with the appropriated cable to the IPFN dsPIC board.
  2. Plug a cable in the input end and connect it to an external voltage source.
  3. Simulate a signal in the range of 0 mV to 4 mV.
  4. Verify values sent by IPFN dsPIC board.

- The second test consists of:
  1. Plug the board with the appropriate cable to the IPFN dsPIC board.
  2. Plug a thermocouple to the input end.
  3. Verify values sent by the IPFN dsPIC board.

The expected signal for both tests is the same as in Figure 4.7. In Section 4.2.2.5, there is further discussion about the expected signal and the description of the calibration method that was used.

### 4.2.2.5 Signal Calibration

Figure 4.7.(a) is an example of the data that is sent to EPICS. As we can observe the average signal, in green, has a better precision than the single discharge plot. All signals have the same time window imposed by the system, the dsPIC board sends a message with the acquisition data every second. For one acquisition the dsPIC takes 0.065 ms, this value was determined taking into account the sampling time and conversion time \( [47] \), multiplied by eight (eight outputs from the thermocouple board), as we can see in equation 4.1.
Table 4.1: ADC configuration, see equation 4.1

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tcy</td>
<td>$3.4 \times 10^{-8}$ s</td>
<td>Clock Period</td>
</tr>
<tr>
<td>ADCS</td>
<td>14</td>
<td>Defines the conversion time</td>
</tr>
<tr>
<td>SAMC</td>
<td>31</td>
<td>Defines the sampling and holding time</td>
</tr>
</tbody>
</table>

Table 4.2: Fit properties of equation 4.2, Figure 4.7.(b)

<table>
<thead>
<tr>
<th>Fit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{env}$ ($K_1$)</td>
</tr>
<tr>
<td>$T_i$ ($K_2$)</td>
</tr>
<tr>
<td>$k$ ($K_3$)</td>
</tr>
<tr>
<td>Average error</td>
</tr>
<tr>
<td>Maximum Deviation</td>
</tr>
</tbody>
</table>

$$T_{acquisiton} = 8.(\frac{Tcy.(ADCS + 1)}{2}SAMC + \frac{Tcy(ADCS + 1)}{2}) \quad (4.1)$$

To get all 1024 acquisitions for the average value, it takes approximately 66.7 ms. The value of 1024 acquisitions was chosen to make the binary division operations easier (only requiring 10 shifts to the right), the error is a statistical one. All data in this sub-chapter are acquired with 1024 acquisitions, unless otherwise specified.

In Figure 4.7.(b) only the cooling curve of ISTTOK is plotted. A fit was done to analyse the decay time of the cooling process and compare it to the average acquisition time. The chosen model, a model called Newton’s law of cooling [48] eq.4.2, assumes only one process of cooling, the convection-cooling.

$$\frac{dT}{dt} = -k(T - T_i) \Leftrightarrow T_{(t)} = T_{env} + (T_i - T_{env})e^{-kt} \quad (4.2)$$

The fit properties support the data albeit with a small deviation (still well in the uncertainty region). The fit’s estimation for the environment temperature is $\approx 100$ ADC units where the experimental data is $\approx 90$ ADC units, this error would probably get attenuated as time went to infinity, the maximum value estimated by the fit is 438 ADC units, where the experimental data is 424 units. Overall this fit is a good approximation of the ISTTOK cooling process. With this fit we can pick the highest decay rate and see how much of a deviation can exist between the first and the last of the 1024 acquisitions required for each point (deviation that occurs in 66.7 ms) $f(0s) - f(66.7ms) = 0.061$. The deviation that occurs in that time is 0.061 ADC units, which being inferior to the ADC resolution\(^1\) implies that any temperature drop occurring during 1024 acquisitions is negligible.

For the error estimation we assumed a worst case scenario and made a rough calculation using the place of the graph, shown in Figure 4.7.(a), with the greatest deviation. The way we made this rough calculation is that we used the last 1024 acquisitions for each point in that area of the graph, and used those to calculate the average deviation.

For the Calibration process, two trials were made. The settings of both trials were similar, two Type

\(^1\) The ADC resolution is 1 ADC’s units.
K thermocouples, inside a closed tube, were used in each trial, one connected to the board, the other to a data Logger thermometer, the RS-1315. This tube was inserted in a kettle, and while the board gave ADC units, the thermometer gave temperature. The difference between both trials is that the second one was made without a lid on the kettle, this was for expediency purposes, since the goal of the second trial was to corroborate the first trial’s results.

In Figure 4.8 in the smaller graphic, two curves are observed, the upward curve reflects heating of the water and the second one, downward, represents the cooling process. The temperature data was taken manually and corresponds to the cooling process.

![Figure 4.8](image)

**Figure 4.8**: This measurement’s goal is to find a relation between the ADC data and temperature, the smaller graphic has all data digitalised by the micro-controller’s ADC through this experiment.

In the first trial, the calibration was done with the kettle’s lid closed, around 50°C and 3000s in the experiment it was briefly removed, this action had more consequences in the measurements than anticipated and can be observed in Figure 4.8a. Also this action contributed to the maximum deviation of 6.3. Nevertheless, the linear fit is quite good, having $R^2 = 0.9989$ and $\chi^2_{red} = 0.014$.

The second trial, clearly had more noise then the first trial, probably due to the different conditions in which this experience was executed. This set-up has a smaller cooling time, probably due to more intense convection currents in the water, causing more oscillation in the thermocouple’s signal. This supposition is supported by the already discussed lid removal “incident” during the first trial.

In Table 4.4 there is a summary of the results from the two experiments, as expected from the observation of Figure 4.8 the mean square error and its standard deviation are smaller in the first experiment than the second, and it is safe to conclude the second experiment represents the worst case scenario. For regular use it is safe to assume the results from the first experiment with a mean square error approximately 3.6 ADC units and have $\Delta{^oC} \approx 3.5$ (ADC units/$^oC$), this means that the system has a precision.
Table 4.4: Thermocouple Calibration Data and Comparison

<table>
<thead>
<tr>
<th></th>
<th>First Trial</th>
<th>Second Trial</th>
</tr>
</thead>
<tbody>
<tr>
<td>m</td>
<td>3.471 ± 0.001</td>
<td>3.390 ± 0.002</td>
</tr>
<tr>
<td>b</td>
<td>91.31 ± 0.06</td>
<td>90.87 ± 0.05</td>
</tr>
<tr>
<td>Mean Square Error</td>
<td>3.6</td>
<td>6.5</td>
</tr>
<tr>
<td>Maximum Deviation to fitted function</td>
<td>6.3</td>
<td>10.8</td>
</tr>
<tr>
<td>Δ°C</td>
<td>3.5</td>
<td>3.4</td>
</tr>
<tr>
<td>Degree Precision</td>
<td>≈1°C</td>
<td>≈2°C</td>
</tr>
<tr>
<td>ADC Precision</td>
<td>8-bit</td>
<td>7-bit</td>
</tr>
<tr>
<td>Degree Resolution</td>
<td>0.29°C</td>
<td>0.29°C</td>
</tr>
</tbody>
</table>

Figure 4.9: The data in graph (a) is taken from the same data in Figure 4.7. As for the data in graph (b), it is taken from the first trial in the calibration process, Figure 4.8 (a).

Figure 4.9: The data in graph (a) is taken from the same data in Figure 4.7. As for the data in graph (b), it is taken from the first trial in the calibration process, Figure 4.8 (a).

(4.2.2.6) Operation conditions

A comparison was done between the normal operation of the developed system during a cleaning discharge and the calibration process.

To collect this data a multimeter was mounted in parallel with the developed board, the results are plotted in Figure 4.9. The results obtained during the cleaning discharge reveal a good signal without many perturbations and a resolution of 8-bits, with the mean square error value even smaller than in the calibration process.

Comparing the calibration fit and the ISTTOK’s cleaning discharge fit, one can observe how well the curves are correlated. The parameter with the highest deviation, is the parameter that gives the difference between the graph and the fit’s zeros, parameter b, but even this is covered by the fit’s standard deviation. It can be concluded from these results that, the system has indeed a 1°C, 8-bit, precision, as expected from the calibration trials.

of 1°C or 8-bits, the system resolution is approximately 0.29°C. In the worst case the system would have a precision of 2°C.
Table 4.5: Thermocouple board in operation conditions, error analyse.

<table>
<thead>
<tr>
<th></th>
<th>During ISTTOK Operation</th>
<th>Frist Trial</th>
</tr>
</thead>
<tbody>
<tr>
<td>m</td>
<td>85.74 ± 0.01</td>
<td>83.9 ± 0.1</td>
</tr>
<tr>
<td>b</td>
<td>88.23 ± 0.002</td>
<td>99.3 ± 0.1</td>
</tr>
<tr>
<td>Mean Square Error</td>
<td>1.4</td>
<td>7.8</td>
</tr>
<tr>
<td>Standard Deviation (σ_{\text{err}})</td>
<td>1.2</td>
<td>2.8</td>
</tr>
<tr>
<td>Maximum Deviation</td>
<td>9.9</td>
<td>7.4</td>
</tr>
<tr>
<td>ΔmlV</td>
<td>85.7</td>
<td>83.9</td>
</tr>
<tr>
<td>mlV Precision</td>
<td>≈0.02</td>
<td>≈0.09</td>
</tr>
<tr>
<td>ADC Precision</td>
<td>8-bit</td>
<td>7-bit</td>
</tr>
<tr>
<td>mlV Resolution</td>
<td>0.01</td>
<td>0.01</td>
</tr>
</tbody>
</table>

4.2.3 Capacitor Bank (ELCO)

4.2.3.1 Introduction

The ELCO is the power source for the primary field and was updated recently [24]. Its properties can be found in Table 4.6. Currently the slow control system and ISTTOK’s operator do not have feedback from this system, therefore an independent system was developed to measure the bank’s voltage. The availability of this information to the operator eases the detection of a malfunction in the bank, since the knowledge of whether a bank can’t either charge or discharge immediately narrows down the possible origins of a malfunction.

This projects required the development of two boards: one to read the signal at the terminals of the ELCO and a second plug-in to the IPFN dsPIC board to receive the signal by fiber optic due to the project’s requirements for insulation. The first board is called the transmitter board and the latter the receiver board.

Table 4.6: Capacitor bank properties

<table>
<thead>
<tr>
<th>Power supply</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal field PS</td>
<td>± 150A</td>
</tr>
<tr>
<td>Vertical field PS</td>
<td>± 450A</td>
</tr>
<tr>
<td>Magnetising field PS</td>
<td>± 350A</td>
</tr>
<tr>
<td>Voltage at the terminals</td>
<td>0V - 300V</td>
</tr>
</tbody>
</table>

4.2.3.2 System Description

The requirements for this project were a high input voltage and an isolated connection to the IPFN dsPIC board, as a note this system was designed to be plugged into the some node board that is reading from the thermocouple system. The connection schematic is similar to the thermocouple system, Figure 4.4, only instead of having thermocouples in the input, it has the capacitor bank terminals and the output for the node board is optical.

It was opted to use an optical connection to the node board, since it guarantees electrical insulation between the two boards. However, this means that the input signal’s differential voltage in the transmitter
board has to be converted into another type of signal. To do this, the NE555 was chosen to modulate a voltage signal into a pulse-position signal. The input for the NE555 requires to have a voltage range from $\frac{1}{3}V_{CC}$ to $\frac{2}{3}V_{CC}$. In this chip the input signal from the input stage is modulated into a pulse-position wave, Figure 4.10 (a) shows the full circuit schematic.

The input stage of the transmitter board, Figure 4.11, receives the signal from the capacitor bank and guarantees a differential high input impedance to ensure a low current drain, in order to decouple the input signal and reject the input’s common noise. It also sets its output range between $\frac{1}{3}V_{CC}$ and $\frac{2}{3}V_{CC}$, in as much as this is the required input by the next stage, the aforementioned conversion stage.

As can be observed in Figure 4.11, this board presents itself as a resistor to the capacitor bank, which implies that this board will slightly discharge the bank over time. The maximum input voltage this board allows is 300 V, at which value the board will drain $\frac{V}{R} \approx 0.15$ mA, and the resistance in the

Figure 4.11: The transmitter board's input stage of the capacitor bank, J2 is the connector to the ELCO
input stage will dissipate a power of 0.045 W. The total resistance in the input stage is a result of three resistances in series, R8, R9 and R10, as can be seen in Figure 4.11, in which voltage across the middle one of the three serves as input to the instrumental amplifier INA129, with a voltage protection to the input. Its gain can be tuned with a trimmer, R5, and has a reference value of \( \frac{1}{3} \cdot V_{CC} \) that fixes the minimum value of \( \frac{1}{3} \cdot V_{CC} \) for the output, with all these features, the output of this stage is given by

\[
V_{out} = \frac{1}{3} \cdot V_{CC} + V_{i} \cdot \text{Gain}.
\]

The input stage’s reference can be trimmed by R11 in Figure 4.11. The buffer is needed because of the low impedance requirement for INA129, a typical requirement for an instrumental amplifier. The board’s full schematic can be found in Figure E.1.

As mentioned before, the optical output is a choice that gives an almost perfect decoupling between this board and the IPFN dsPIC board. The emitter and receiver chosen for the fiber optic were the HFBR1521 and the HFBR2521, respectively, fulfilling all of the requirements, at low cost. However, the IPFN dsPIC board does not have support for this type of fiber optic, therefore the necessity to develop another board, in order to make the IPFN dsPIC board compatible.

The receiver board was developed to dock and connect with the IPFN dsPIC board eurocard connector, therefore one of its sides must have 100mm, although the other side is smaller, with about 50mm. With this choice of dimensions, it is possible to dock the board into the IPFN dsPIC board without significantly increasing the size. The final design of this board has: 4 optic receivers connected to pins CN1/TX1 (change notification/UART 1 receiver), CN7, IC1 (input capture) and IC2; A connector with 16 connections to the dsPIC ADC, ground and VCC; Two transmitters, one is connected to TX1 (UART 1 transmitter) or OC3 (output compare) depending on the choice made, using a jumper, the other transmitter is connected to OC4, for a better understanding see Figure E.2. This last board is also used to connect the thermocouple board to the node as it is the same node receiving from both systems.

### 4.2.3.3 Transmitter Board Assembly

In a similar manner as before, with the other developed board, the development of this new board can be divided into stages. Similarly to what was done in the first stage of development of the previous board, a test was performed in a bread board with a wide variety of designs and opted for the one already describe in Section 4.2.3.2. However, this board also requires to be powered up by the grid, hence a power source stage was designed, consisting of a VCC at 5 V and an unregulated VCC at 7.5 V, connected to the grid by a transformer.

The second stage is the assembly stage, where the PCB layout was projected, Figure 4.11. This board is projected to be stored inside a box with the following dimensions: 112 mm × 62 mm × 31 mm. The ground plane was partially removed from the input stage area, due to the high voltage amplitude of this area of the board, thus avoiding discharges through the board’s ground.

This board is projected to be a single layer although at the time the laboratory had only dual layer boards in stock. In the final design, the board come up with two layers and the dimensions 109 mm × 59 mm.

It takes roughly four hours to assemble this board and its components, with a total cost of \( \approx \in 16 \).
Figure 4.12: PCB of the capacitor bank board. The light red via is the transformer source at 9V. The dark red is the unregulated vcc at 9V. The orange is the vcc at 5V. The blue via is the reference, the ground. The rest of the vias, in yellow, are the signal connections. The input stage schematic is in Figure 4.11 and in Figure 4.10 is the schematic for the conversion stage and optical stage. The source stage is only represented in Figure E.1.

Table E.1 can give a more detailed information about the material cost.

### 4.2.3.4 Testing The Transmitter Board

One test was done to these boards, to ensure that all stages were operating properly and safely.

The first step is to verify that the input stage is working correctly. To do this, a multimeter, an oscilloscope and a variable power source between 0 V and 300 V were used. The power source will be used as the input signal, connected to J2 and the multimeter or oscilloscope to J4, Figures 4.11 and 4.11. If the aforementioned power source supplies high current and some touches the board when the input source is ON, there could be hazardous consequences. The signal should evolve the same way as the input, having a multiplying factor, since instead of having a range of 0 V to 300 V as the input, its signal has a range between 0 and 4V. Nevertheless the signal conversion should be linear. The expected range depends on two adjustments that can be done in the board: the first is a gain adjustment, R6, and the other is a reference adjustment, R11. In spite of these adjustments, which allow a broader range, the maximum range should be between $\frac{1}{3}vcc$ and $\frac{2}{3}vcc$ due to the restrictions previously described.

The second step is an examination of the frequency range of the NE555 output. Assuming that the signal range limit in the stage input is not exceeded, the frequency range must be between 22k Hz and 30k Hz.

In the last step it is checked the optical stage. It will require an optic receiver and a cable 11 m long. Regardless of whether there is an input or not, if the board is ON, the optic receiver should get a frequency that must be equal to the one transmitted by the board.
4.2.3.5 Receiver Board Assembly

The assembly of the transmitter board was not yet complete, according to the prerequisites for this project.

Note that only some of the I/Os (input/output) of the eurocard connector to link to the transmitter board IPFN dsPIC board were used and some of the unused pins of this eurocard connector were removed, as can be seen in Figure 4.13.

Presently the sixteen pin connector is connected to the thermocouple board and one optic receiver was assembled and connected to the transmitter board of ELCO. The remaining receivers were not assembled as well as the HBFR1521 fiber optic transmitter.

In the assembling of the remaining components, there are two choices to make. The first is related to the assembling of the fiber optic receiver HFBR2521 and either assemble the resistor’s group, R1, R3, R5 and R7 or he resistor’s group, R2, R4, R6 and R8. The second choice, done when assembling the optic transmitter, the value of R9 and R10 can be changed to meet led intensity requirements of the HFBR1521.

The total cost of the material to fully assemble this board is approximately €77, however the cost of the partial assembly that was done, was around €18.

4.2.3.6 Testing the Receiver board

Three different tests are recommended for this board, one to the ADC inputs, one to test the optic receivers and one for the optic transmitter. To perform all the tests, it is required to have a multimeter or oscilloscope and the IPFN dsPIC board. A breadboard is also required, as well as a potentiometer and some wires to test the ADC inputs.

It is possible to assess the VCC, the ground and respective ADC input from the 16 pins connector if everything is working as expected. The digitalised signal should be similar to the drop voltage in the potentiometer, that can be followed with the multimeter or the oscilloscope.
Figure 4.14: In graphic (a) it is plotted the raw data acquisition from the capacitor bank for one discharge and graphic (b) has the same data but it was done a moving average of the data.

To test the optical receiver an optic fiber cable and a optic transmitter are required. In this test, using an oscilloscope or the IPFN dsPIC board, is possible to examine the electrical pulse generated in the receiver, from the signal sent by the optic transmitter.

Finally to test the transmitters, it is programmed in the micro controller of the IPFN dsPIC board to generate pulses and an optic receiver should receive them.

4.2.3.7 Signal

The data sent by the node to EPICS is a value representing a wave's period and is measured every second. However, during the final test to the capacitor board, an anomalous signal was detected. In Figure 4.14 (a) it is plotted a discharge of the capacitor bank and as can be observed the signal has an upper bound and a lower bound. This signal appears to be a result of a mix of three distinct signals and in Figure 4.14 (b) is plotted a moving average revealing a wave. This means that frequency receive a systematic variation and probably the voltage signal before being converted to frequency.

After a meticulous examination of all possible origins of this error, it due of the board's ground being decoupled from the signal ground and also due to the high amplitude of the input signal. Consequently, these two contributions make the amplifier saturate in both limits simulating a maximum curve and a minimum curve, as the acquire data has.

The best approach to solve this is to redesign the input stage of the circuit to a differential amplifier scheme. Other solutions were tried but none succeeded.

4.2.4 Gallium experiment

The set-up of the gallium experiment, described in Section 1.4.2.4, was conceptualized in 2006 and has been developed and improved. The intention of this experiment is to study the gallium-plasma interactions.
In this project, this experiment was integrated into the EPICS system, since this experiment was already using an IPFN dsPIC board even though it was required to make some changes in the firmware.

This experiment has 8 temperature sensors and 4 valves, depicted in Figure 1.6, the information from the sensors flows from the node to EPICS, which is not the case for the valves since they need to be controlled by the user/operator through EPICS. In the latter case, the node sends the information about valve status to EPICS every second. Then, when necessary, EPICS sends the command to change the valve's state. In Figure 1.6 it is illustrated the physical set-up and the location of sensors and valves that interact with EPICS, in Table A.3 the created PVs and in Figure B.2 the developed GUI for this experiment are presented.
Chapter 5

Conclusions

During this thesis it was possible to developed a system prototype for the ISTTOK slow control system. This system is still in development stage but shows promising signs and is important to ISTTOK to have a substitute.

This system fulfils all the ISTTOK necessities in reliability, resilience and can surpass all the limitations of the installed one. The external connectivity is not only possible but is nativity implemented through CA protocol, connectivity through other protocol is also possible but is require little more work. Presently it has its own database though in future it can be integrated with the ISTTOK database that uses the PostgreSQL technology. This new control system is based on modular concept and distribute control, it supports several control unit sharing information between them. It has compatibility with the installed systems, in the case of fast control communication specially with MARTe there is already integration, it is possible to configure MARTe and read its variables through the CA. It has modern programmable language, all documentation and source code are available as all system is based on freeware though documentation sometimes can is not the best and it terms of supports the ITER community can always give a hand. Another problem of the slow control unit in use is its hardware, however in concept of the new system this problem do not exist, due its software approach. It can run in any computer provide that has an operating system, Perl, GNU make and C++.

The alarm system in place in the new slow control system can improve the ISTTOK security due to its better ingratiation with the fast system. With this new system it becomes easier and faster to the Operator to detect and acknowledge a problem, even a minor one.

In the prototype control unit was integrated three nodes. One was develop on house to measure the temperature of ISTTOK’s shell and voltage of the ELCO. The temperature measuring met the expected precision and with this system is now possible to easily track the shell temperature. The measuring of ELCO’s voltage has a problem with the acquire signal and its electric schematic needs to revise, its problem derives from both grounds are totally decouple some workarounds were tried however without any result, probably the resolution for this problem will be a redesign of electric schematic and change the input stage. The vacuum node and the gallium node are acquiring without any complication for some time now, and their values are also being archiving.
5.1 Future Work

The next step for this project should be the improvement of the state machine with it start deciding and implementing input variables that should work as conditions to change between states. Then the implementation of the output PV should take place, without any connection to world, dummy PV and verify that all work correctly. It also should be test system response in case of abortion or emergency.

The archive system should be upgraded to be integrated with the ISTTOK database. This mean that an interface with the FireSignal middleware has to be develop.

The communication with the fast control has to be also implemented though there are some work than in this area. This way smoother integration with the fast control system, would be possible.

It possible to developed OPI to be access by a browser to accomplish that first is needed to solve the compatibility problems between the Java, the OPIs and tomcat.

In parallel with each integration is necessary to develop a GUI for it or integrate the new information in a existing OPI.

The ISTTOK alarms should also be integrate in the new control system, this integration allows a broader use of them, an example is the sound alarm that can be trigger in emergency. It can be also implement in the new slow control unit a state notification through email if a major alarm is trigger providing a faster response from the ISTTOK team.
Bibliography


## Appendix A

### EPICS, PV List

#### Table A.1: List of the running PV of the vacuum node in the prototype for the new slow control unit

<table>
<thead>
<tr>
<th>PV name</th>
<th>PV type</th>
<th>Archive</th>
</tr>
</thead>
<tbody>
<tr>
<td>ISTTOK:vacuum:Uptime</td>
<td>longin</td>
<td>no</td>
</tr>
<tr>
<td>ISTTOK:vacuum:Diff_Uptime</td>
<td>calc</td>
<td>no</td>
</tr>
<tr>
<td>ISTTOK:vacuum:Last_Update</td>
<td>calc</td>
<td>no</td>
</tr>
<tr>
<td>ISTTOK:vacuum:Pressure_Chamber1</td>
<td>ai</td>
<td>yes</td>
</tr>
<tr>
<td>ISTTOK:vacuum:Pressure_Primary1</td>
<td>ai</td>
<td>yes</td>
</tr>
</tbody>
</table>

#### Table A.2: List of the running PV of the temperature node in the prototype for the new slow control unit

<table>
<thead>
<tr>
<th>PV name</th>
<th>PV type</th>
<th>Archive</th>
</tr>
</thead>
<tbody>
<tr>
<td>ISTTOK:temperature:Uptime</td>
<td>longin</td>
<td>no</td>
</tr>
<tr>
<td>ISTTOK:temperature:Diff_Uptime</td>
<td>calc</td>
<td>no</td>
</tr>
<tr>
<td>ISTTOK:temperature:Last_Update</td>
<td>calc</td>
<td>no</td>
</tr>
<tr>
<td>ISTTOK:temperature:RawTemperature.0</td>
<td>ai</td>
<td>yes</td>
</tr>
<tr>
<td>ISTTOK:temperature:Temperature.0</td>
<td>calc</td>
<td>yes</td>
</tr>
<tr>
<td>ISTTOK:temperature:RawTemperature.1</td>
<td>ai</td>
<td>no</td>
</tr>
<tr>
<td>ISTTOK:temperature:Temperature.1</td>
<td>calc</td>
<td>no</td>
</tr>
<tr>
<td>ISTTOK:temperature:RawTemperature.1</td>
<td>ai</td>
<td>no</td>
</tr>
<tr>
<td>ISTTOK:temperature:Temperature.1</td>
<td>calc</td>
<td>no</td>
</tr>
<tr>
<td>ISTTOK:temperature:RawTemperature.2</td>
<td>ai</td>
<td>no</td>
</tr>
<tr>
<td>ISTTOK:temperature:Temperature.2</td>
<td>calc</td>
<td>no</td>
</tr>
<tr>
<td>ISTTOK:temperature:RawTemperature.2</td>
<td>ai</td>
<td>no</td>
</tr>
<tr>
<td>ISTTOK:temperature:Temperature.2</td>
<td>calc</td>
<td>no</td>
</tr>
<tr>
<td>ISTTOK:temperature:RawCapbank_Voltage</td>
<td>ai</td>
<td>no</td>
</tr>
<tr>
<td>ISTTOK:temperature:Capbank_Voltage</td>
<td>calc</td>
<td>no</td>
</tr>
</tbody>
</table>
### Table A.3: List of the running PV of the gallium node in the prototype for the new slow control unit

<table>
<thead>
<tr>
<th>PV name</th>
<th>PV type</th>
<th>Archive</th>
</tr>
</thead>
<tbody>
<tr>
<td>ISTTOK:gallium:Uptime</td>
<td>longin</td>
<td>no</td>
</tr>
<tr>
<td>ISTTOK:gallium:Diff_Uptime</td>
<td>calc</td>
<td>no</td>
</tr>
<tr>
<td>ISTTOK:gallium:Last_Update</td>
<td>calc</td>
<td>no</td>
</tr>
<tr>
<td>ISTTOK:gallium:Temperature_0</td>
<td>ai</td>
<td>yes</td>
</tr>
<tr>
<td>ISTTOK:gallium:Temperature_1</td>
<td>ai</td>
<td>yes</td>
</tr>
<tr>
<td>ISTTOK:gallium:Temperature_2</td>
<td>ai</td>
<td>yes</td>
</tr>
<tr>
<td>ISTTOK:gallium:Temperature_3</td>
<td>ai</td>
<td>yes</td>
</tr>
<tr>
<td>ISTTOK:gallium:Temperature_4</td>
<td>ai</td>
<td>yes</td>
</tr>
<tr>
<td>ISTTOK:gallium:Temperature_5</td>
<td>ai</td>
<td>yes</td>
</tr>
<tr>
<td>ISTTOK:gallium:Valve_1</td>
<td>bo</td>
<td>no</td>
</tr>
<tr>
<td>ISTTOK:gallium:Valve_1_RBV</td>
<td>bi</td>
<td>no</td>
</tr>
<tr>
<td>ISTTOK:gallium:Valve_2</td>
<td>bo</td>
<td>no</td>
</tr>
<tr>
<td>ISTTOK:gallium:Valve_2_RBV</td>
<td>bi</td>
<td>no</td>
</tr>
<tr>
<td>ISTTOK:gallium:Valve_3</td>
<td>bo</td>
<td>no</td>
</tr>
<tr>
<td>ISTTOK:gallium:Valve_3_RBV</td>
<td>bi</td>
<td>no</td>
</tr>
<tr>
<td>ISTTOK:gallium:Valve_4</td>
<td>bo</td>
<td>no</td>
</tr>
<tr>
<td>ISTTOK:gallium:Valve_4_RBV</td>
<td>bi</td>
<td>no</td>
</tr>
</tbody>
</table>

### Table A.4: List of the running PV of the state machine developed in the prototype for the new slow control unit

<table>
<thead>
<tr>
<th>PV name</th>
<th>PV type</th>
<th>Archive</th>
</tr>
</thead>
<tbody>
<tr>
<td>ISTTOK:central:AUTHORISATION</td>
<td>bo</td>
<td>no</td>
</tr>
<tr>
<td>ISTTOK:central:OPREQ</td>
<td>bo</td>
<td>no</td>
</tr>
<tr>
<td>ISTTOK:central:PROCESS-MODE</td>
<td>bo</td>
<td>no</td>
</tr>
<tr>
<td>ISTTOK:central:PROCESS-REQ</td>
<td>bo</td>
<td>no</td>
</tr>
<tr>
<td>ISTTOK:central:COUNTER</td>
<td>calc</td>
<td>no</td>
</tr>
<tr>
<td>ISTTOK:central:OPCALCSTATE</td>
<td>calc</td>
<td>no</td>
</tr>
<tr>
<td>ISTTOK:central:COUNTDOWN</td>
<td>mbbi</td>
<td>no</td>
</tr>
<tr>
<td>ISTTOK:central:PULSE-NUMBER</td>
<td>longout</td>
<td>no</td>
</tr>
<tr>
<td>ISTTOK:central:OPSTATE</td>
<td>logout</td>
<td>no</td>
</tr>
<tr>
<td>ISTTOK:central:CurrentTime</td>
<td>stringin</td>
<td>no</td>
</tr>
<tr>
<td>ISTTOK:central:TraceMessage</td>
<td>stringout</td>
<td>no</td>
</tr>
</tbody>
</table>
Appendix B

Graphical User Interface

Figure B.1: The ISTTOK menu GUI
Figure B.2: The developed GUI for gallium experiment
Figure B.3: ISTTOK main panel GUI
Figure B.4: A full screen GUI developed to show to the personal present in the laboratory.
Appendix C

State Machine code

program IsttokSeqExec

double v;
assign v to "{unit}:gallum:tesi.ai";
monitor v;

/* ISTTOK Array of Operating State PV – MBBI records */
short IsttokOPSTATE[1];
assign IsttokOPSTATE to {
"{unit}:central:OPSTATE"
};
monitor IsttokOPSTATE;

/* ISTTOK Operation Request */
short IsttokOPREQ[1];
assign IsttokOPREQ to {
"{unit}:central:OPREQ"
};
monitor IsttokOPREQ;

/* ISTTOK Plasma Process Mode */
short IsttokProcMode;
assign IsttokProcMode to "{unit}:central:PROCESS-MODE";
monitor IsttokProcMode;

/* ISTTOK Plasma Process Request */
short IsttokProcReq;
assign IsttokProcReq to "{unit}:central:PROCESS-REQ";
monitor IsttokProcReq;

short POS_Stopped;
short POS_Starting;
short POS_Process;
short POS_Clean;
short POS_WaitShot;
short POS_Stopping;

/* Constants */
short ON;
short OFF;
short START;
short STOP;
short CLEAN;
short SHOT;
short NO_ALARM;
short MINOR;
short MAJOR;
short INVALID;

/* Trace message record limited to 40 characters */
string msg;
    assign msg to "{unit}:central:TraceMessage.VAL";
monitor msg;

ss PulseSequence {
    state init {
        entry {
            /* Initialisation of constants and indexes */
            POS_Stopped =0;
            POS_Start=1;
            POS_Process =2;
            POS_Clean =3;
            POS_WaitShot=4;
            POS_Stopping=5;

            ON=1; OFF=0;
            START=1; STOP=0;
            SHOT=1; CLEAN=0;

            NO_ALARM=0; MINOR=1; MAJOR=2; INVALID=3;

            strcpy(msg, "Pulse Sequence entry");
            pvPut(msg);
            errlogSevPrintf(NO_ALARM, "%s\n",msg);
        }

        when (delay(5)) {
            printf("IsttokSeqExec: Startup delay over\n");
        }
    }

    // State Set Stopped */
    state Stopped {
        when ((IsttokOPREQ[0]==START)) {
            strcpy(msg, "Pulse State Starting");
            pvPut(msg);
            errlogSevPrintf(NO_ALARM, "%s\n",msg);

            /* Pulse state change to Starting */
            IsttokOPSTATE[0] = POS_Start;
            pvPut(IsttokOPSTATE[0]);
        } state Starting
    }

    // State Set Starting */
    state Starting {
        when ((IsttokOPREQ[0]==STOP)) {
            strcpy(msg, "Pulse State to Stopping");
            pvPut(msg);
            errlogSevPrintf(MINOR, "%s\n",msg);

            /* Pulse state change to Stopping */
            IsttokOPSTATE[0] = POS_Stopping;
            pvPut(IsttokOPSTATE[0]);
        } state Stopping
    }

    when (delay(5.0)) {
        strcpy(msg, "Pulse State to Process");
    }
}
/* Pulse state change to Stopped */
IsttokOPSTATE[0] = POS_Process;
pvPut(IsttokOPSTATE[0]);
} state Process

/* State Set Process */
state Process {
    when ((IsttokOPREQ[0]==STOP)) {
        strcpy(msg, "Pulse State to Stopping");
pvPut(msg);
        errlogSevPrintf(NO_ALARM, "%s\n",msg);
        /* Pulse state change to Stopping */
        IsttokOPSTATE[0] = POS_Stopping;
pvPut(IsttokOPSTATE[0]);
    } state Stopping

    when ((IsttokProcReq==START) && (IsttokProcMode==CLEAN)) {
        strcpy(msg, "Pulse State to Clean");
pvPut(msg);
        errlogSevPrintf(NO_ALARM, "%s\n",msg);
        /* Pulse state change to Clean */
        IsttokOPSTATE[0] = POS_Clean;
pvPut(IsttokOPSTATE[0]);
    } state Clean

    when ((IsttokProcReq==START) && (IsttokProcMode==SHOT)) {
        strcpy(msg, "Pulse State to WaitShot");
pvPut(msg);
        errlogSevPrintf(NO_ALARM, "%s\n",msg);
        /* Pulse state change to WaitShot */
        IsttokOPSTATE[0] = POS_WaitShot;
pvPut(IsttokOPSTATE[0]);
    } state WaitShot

} state Clean {
    when ((IsttokOPREQ[0]==STOP) || (IsttokProcReq==STOP)) {
        strcpy(msg, "Pulse State to Process");
pvPut(msg);
        errlogSevPrintf(NO_ALARM, "%s\n",msg);
        /* Just to be sure */
        IsttokProcReq = STOP;
pvPut(IsttokProcReq);
        /* Pulse state change to Process */
        IsttokOPSTATE[0] = POS_Process;
pvPut(IsttokOPSTATE[0]);
    } state Process

} state WaitShot {
    when ((IsttokOPREQ[0]==STOP) || (IsttokProcReq==STOP)) {
        strcpy(msg, "Pulse State to Process");
pvPut(msg);
errlogSevPrintf(NO_ALARM, "%s\n", msg);

/* Just to be sure */
IsttokProcReq = STOP;
pvPut(IsttokProcReq);

/* Pulse state change to Process */
IsttokOPSTATE[0] = POS_Process;
pvPut(IsttokOPSTATE[0]);
} state Process

/* State Set Stopping */
state Stopping {
when (delay (5.0)) {
    strcpy(msg, "Pulse State to Stopped");
pvPut(msg);
    errlogSevPrintf(NO_ALARM, "%s\n", msg);
    IsttokOPREQ[0]=STOP;
pvPut(IsttokOPREQ[0]);

    /* Pulse state change to Stopping */
    IsttokOPSTATE[0] = POS_Stopping;
pvPut(IsttokOPSTATE[0]);

    /* Pulse state change to Stopped */
    IsttokOPSTATE[0] = POS_Stopped;
pvPut(IsttokOPSTATE[0]);
} state Stopped
}
## Appendix D

### Thermocouple project

Table D.1: Thermocouple material list

<table>
<thead>
<tr>
<th>Item</th>
<th>Reference</th>
<th>Qty.</th>
<th>Part</th>
<th>Price Per Unit</th>
<th>Farnell Code</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>C1,C2,C3,C4,C5,C6,C7,C8</td>
<td>8</td>
<td>220μF</td>
<td>€0.008</td>
<td>1759373</td>
<td>€0.064</td>
</tr>
<tr>
<td>2</td>
<td>C9,C10,C11,C12,C13,C14,C15,C16</td>
<td>8</td>
<td>100μF</td>
<td>€0.003</td>
<td>1709894</td>
<td>€0.024</td>
</tr>
<tr>
<td>3</td>
<td>J1, Molex 3 Pins</td>
<td>4</td>
<td>CON16</td>
<td>€0.390</td>
<td>1708087</td>
<td>€1.560</td>
</tr>
<tr>
<td>4</td>
<td>J1, Molex 2 Pins</td>
<td>2</td>
<td>CON16</td>
<td>€0.220</td>
<td>1624287</td>
<td>€0.440</td>
</tr>
<tr>
<td>5</td>
<td>R1,R2,R9,R10,R15,R16,R21,R22,R27, R28,R33,R34,R39,R40,R45,R46</td>
<td>16</td>
<td>300Ω</td>
<td>€0.003</td>
<td>1799340</td>
<td>€0.048</td>
</tr>
<tr>
<td>6</td>
<td>R3,R4,R11,R12,R17,R18,R23,R24,R29, R30,R35,R36,R41,R42,R47,R48</td>
<td>16</td>
<td>300kΩ</td>
<td>€0.003</td>
<td>1646211</td>
<td>€0.048</td>
</tr>
<tr>
<td>7</td>
<td>R5,R6,R7,R8,R13,R14,R19,R20,R25, R26,R31,R32,R37,R38,R43,R44</td>
<td>16</td>
<td>510kΩ</td>
<td>€0.002</td>
<td>2350850</td>
<td>€0.032</td>
</tr>
<tr>
<td>8</td>
<td>R49,R50,R51,R52,R53,R54,R55,R56</td>
<td>8</td>
<td>5.1kΩ</td>
<td>€0.002</td>
<td>2413708</td>
<td>€0.016</td>
</tr>
<tr>
<td>9</td>
<td>U1,U2,U3,U4,U5,U6,U7,U8</td>
<td>8</td>
<td>LM358</td>
<td>€0.265</td>
<td>2295980</td>
<td>€2.120</td>
</tr>
<tr>
<td>10</td>
<td>U1,U2,U3,U4,U5,U6,U7,U8</td>
<td>8</td>
<td>Socket</td>
<td>€0.550</td>
<td>1183596</td>
<td>€4.400</td>
</tr>
<tr>
<td>11</td>
<td>PCB Dual Layer 200x300mm</td>
<td>0.17</td>
<td>Copper</td>
<td>€9.660</td>
<td>1267752</td>
<td>€1.642</td>
</tr>
</tbody>
</table>

Total: €12.954
Figure D.1: Thermocouple board schematic
# Appendix E

## Capacitor Bank

Table E.1: Material list for the transmitter board for Capacitor Bank

<table>
<thead>
<tr>
<th>Item</th>
<th>Reference</th>
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Figure E.1: capacitor bank board schematic
Figure E.2: Adaptor board schematic