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A Distributed Monitoring and Control System for the Laser Ion Source RILIS at CERN-ISOLDE

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Abstract

In this work, the implementation of the LabVIEW-based *RILIS Equipment Acquisition and Control Toolset* (REACT) software framework is documented, revised, and further developed to accomplish remotely operated in-source laser spectroscopy experiments at CERN-ISOLDE.

The *Resonance Ionization Laser Ion Source* (RILIS) is an integral part of the radioactive ion beam user facility ISOLDE at CERN. Its task as an ion source is to ensure high isobaric purity and production efficiency of the ion beams that are generated for the various experimental setups of the facility. Reliable operation requires directing 3 pulsed laser beams, precisely wavelength-tuned and overlapped in time to a precision of 5 nanoseconds, to converge into a 3 mm diameter ion source cavity located 25 m away in an inaccessible radioactive environment. These stable conditions have to be maintained for up to 7 days at a time per experiment setup. Within recent years, the array of RILIS equipment and its need to interface with other experimental apparatus outside of the laser laboratory has steadily grown. This has increased the demand for developing software to address machine supervision and data acquisition tasks, as well as installing automated safety systems.

In order to meet these demands, a distributed monitoring and control system was commissioned and continually developed since 2011, which focuses on modularity and flexibility to adapt to changing experiment requirements. The system is implemented using the data-flow oriented graphical programming language LabVIEW and makes extensive use of the integrated shared variable technology to facilitate network data communication.

The presented work documents the conceptual design, implementation details and newly developed functionalities for programs currently available to the RILIS operators to support the setup and operation of the laser ion source equipment. Moving the supervisory control of the RILIS installation to a separate building outside the designated radiation supervised ISOLDE hall area has compounded the need for commissioning a new control room and implementing comprehensive remote monitoring, control, and automation programs for the crucial laser parameters. In the course of this thesis work, this entailed the development of stabilization programs for the laser power, laser timing, and the laser wavelength. Additional software components have been refactored and extended to make use of the modular and extensible structure of the equipment communication programs within the REACT framework.

These developments have enabled the RILIS operators to conduct in-source laser spectroscopy experiments, one of the most demanding objectives, remotely from the newly commissioned control room, representing a significantly improved and ergonomic work environment. In addition to permitting remote operation, the increased automation of the system has enabled the transition from shift work to monitored on-call operation as the standard for 2015.

Zusammenfassung

In dieser Arbeit wird die Implementierung des LabVIEW-basierten *RILIS Equipment Acquisition and Control Toolset* (REACT) Software-Frameworks dokumentiert, überarbeitet und weiterentwickelt, um die fern-überwachte Durchführung von In-Source Laserspektroskopie-Experimenten bei CERN-ISOLDE zu ermöglichen.

Die *Resonance Ionization Laser Ion Source* (RILIS) ist ein integraler Bestandteil der ISOLDE Forschungseinrichtung zur Erzeugung radioaktiver Ionenstrahlen am CERN. Aufgabe der RILIS als Ionenquelle ist es, hohe isobare Reinheit und Produktionseffizienz der Ionenstrahlen zu gewährleisten, die für die verschiedenen Versuchsanordnungen der Anlage erforderlich sind. Der zuverlässige Betrieb erfordert, dass 3 gepulste Laserstrahlen, präzise in der Wellenlänge abgestimmt und zeitlich auf 5 Nanosekunden genau überlagert, in einer Ionenquelle mit 3 mm Durchmesser konvergieren, die 25 m weit entfernt in einer unzugänglichen radioaktiven Umgebung gelegen ist. Diese stabilen Betriebsbedingungen sind für bis zu 7 Tage pro Experiment kontinuierlich aufrecht zu erhalten. In den letzten Jahren ist sowohl die Anzahl der zum Betrieb der RILIS notwendigen Gerätschaften, als auch die Notwendigkeit des Datenaustauschs mit weiteren Forschungsaufbauten außerhalb des Laserlabors stetig gewachsen. Dies erforderte die Entwicklung und Einrichtung von Systemen zur Maschinenüberwachung und -steuerung, zur Datenaufnahme, sowie die Installation automatischer Sicherheitssysteme.

Um diese Anforderungen zu erfüllen, wurde im Jahr 2011 ein verteiltes Überwachungs- und Steuerungssystem in Betrieb genommen und seither mit dem Fokus auf Modularität und Flexibilität kontinuierlich weiterentwickelt, um Anpassungen an sich ändernde experimentelle Anforderungen zu ermöglichen. Das System ist in der Datenfluss-orientierten grafischen Programmiersprache LabVIEW implementiert und nutzt die dort integrierte Technologie der Netzwerk-Umgebungsvariablen zur Datenkommunikation.

Die vorliegende Arbeit dokumentiert den konzeptionellen Entwurf, die Implementierungsdetails und neu entwickelte Funktionalitäten der Programme, die den Physikern der RILIS jetzt zur Verfügung stehen, um die Einrichtung und den Betrieb der Laserionenquelle zu unterstützen. Die Verlagerung der Überwachungssteuerung der RILIS Installation in ein separates Gebäude außerhalb der ausgewiesenen radioaktiven Kontrollzone der ISOLDE Halle erforderte die Einrichtung eines neuen Kontrollraums als Fern-Leitwarte und einem umfassenden Überwachungs- und Steuerungssystem für alle wesentlichen Laserparameter. Im Rahmen dieser Arbeit wurden zu diesem Zweck neue Programme zur Stabilisierung der Laserleistung, des Laser-Timings und der Laserwellenlänge implementiert. Weitere Softwarekomponenten wurden umgestaltet und erweitert, um so eine bessere Modularisierung und Erweiterbarkeit der Programme im REACT Framework zu gewährleisten.

Diese Entwicklungen ermöglichen es den Betreibern der RILIS, In-Source Laserspektroskopie-Experimente, eine der anspruchsvollsten Arbeitsaufgaben, ferngesteuert aus dem neuen Kontrollraum durchzuführen, was einen wesentlichen Schritt zu einer verbesserten, ergonomischen Arbeitsumgebung darstellt. Zusätzlich zur Fernsteuerung hat der erhöhte Grad der Automatisierung den Wechsel vom Schichtbetrieb hin zur Rufbereitschaft als Standard-Betriebsart ab dem Jahr 2015 ermöglicht.

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Contents

1 Introduction

This chapter provides a brief introduction of the ISOLDE (*Isotope Separator On-Line DEvice*)[1][2] radioactive ion beam facility located at CERN (*Conseil Européen pour la Recherche Nucléaire*)[2] and outlines the working principle and operational tasks for the *Resonance Ionization Laser Ion Source* (RILIS) as the primary ion source of ISOLDE.

1.1 The ISOLDE Facility at CERN

The CERN accelerator complex shown in Figure 1 consists of several interconnected facilities dedicated to specific fields of fundamental research in nuclear and particle physics.

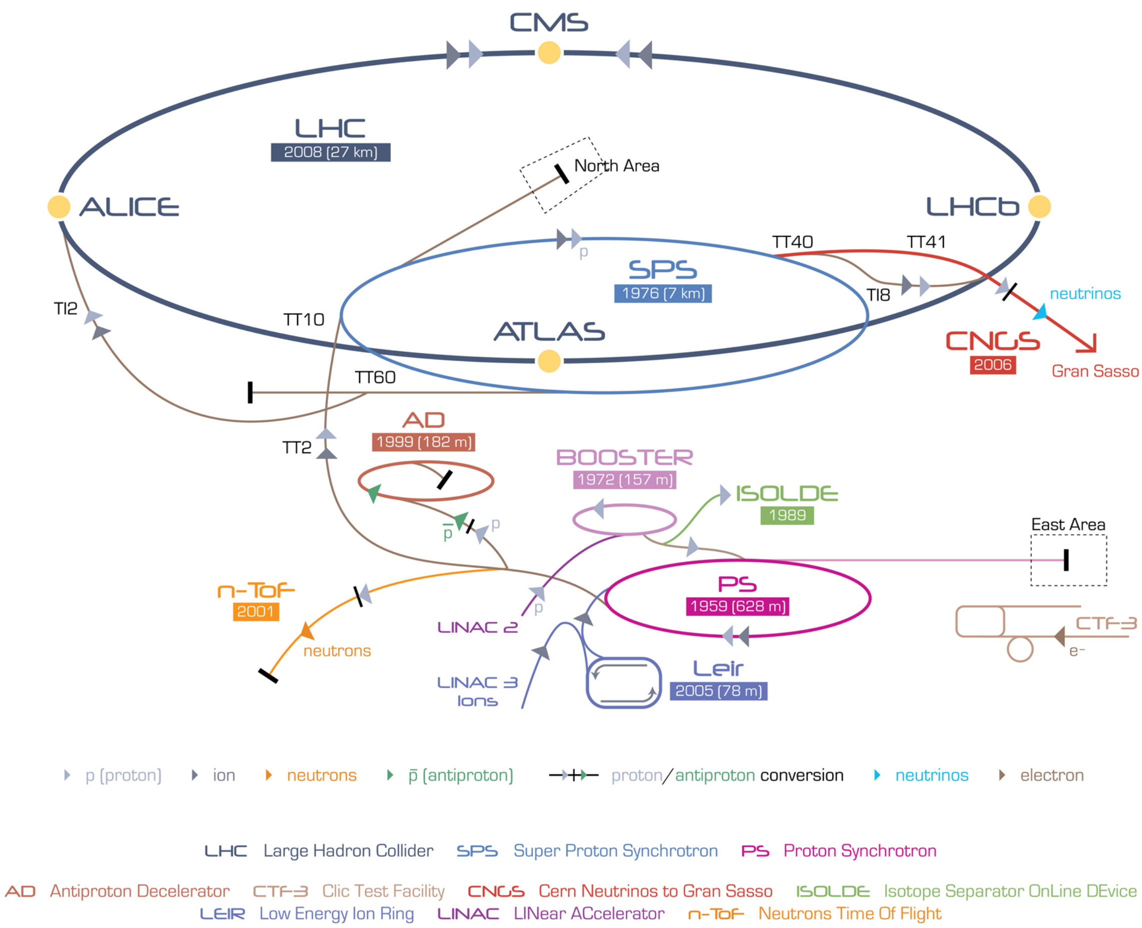

Figure 1: Schematic overview of the CERN accelerator complex. [3], [4]

[1]Founded as *Isotope Separator On-Line DEtector* [1]
[2]International: *European Organization for Nuclear Research*

The primary purpose of the ISOLDE user facility is the production of ion beams of rare, short-lived radioactive isotopes and the study of their fundamental properties. For this purpose, local experiment collaborations and user groups from various research institutions around the globe formulate detailed proposals to the *ISOLDE and Neutron Time-of-Flight experiments Committee* (INTC) which allocates beam time for the production of specific isotopes of interest to be studied.

Once the beam time is granted and scheduled into the yearly physics program, a specific target unit is prepared as the source for the radioactive ion beam. This target unit receives a beam of high energy protons via a direct connection between the ISOLDE facility and the *Proton Synchrotron Booster* (PSB). The protons impinge on a thick target and produce a multitude of different isotopes within the material through various nuclear reaction channels [5]. The reaction products are typically ionized inside a hot tubular cavity attached to the target unit and are subsequently extracted by the electrostatic field from the 60 kV acceleration potential. The resulting ion beam is directed through either one (*General Purpose Separator*, GPS) or two (*High Resolution Separator*, HRS) dipole separator magnets to select isotopes of a specific mass, which are then distributed to various experimental setups. A schematic overview of the ISOLDE target area, the two available separator setups, and the ion beamline connections is shown in Figure 2.

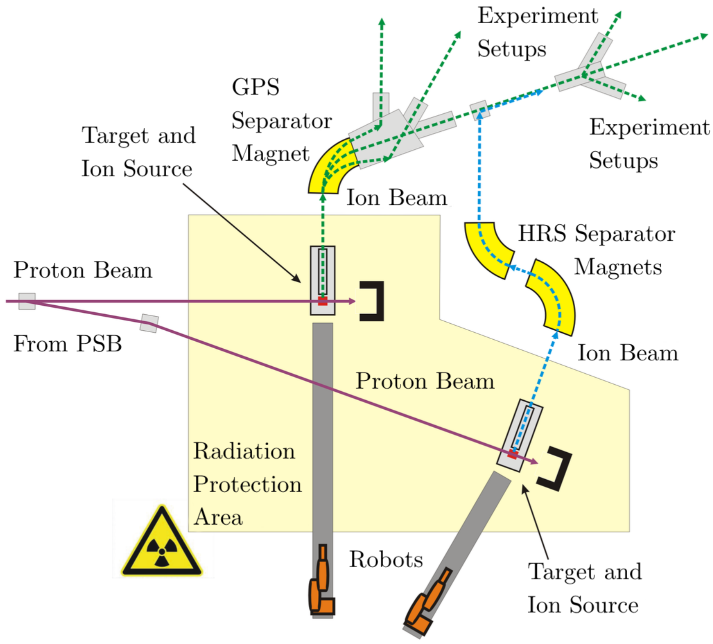

Figure 2: Schematic overview of the ISOLDE target area, separator setups, and ion beamline connections. (Image adopted and modified from [6])

1.2 The Resonance Ionization Laser Ion Source RILIS

The *Resonance Ionization Laser Ion Source* (RILIS) of ISOLDE is a specialized setup for ion generation, which complements the magnetic mass separation by performing highly selective laser excitation and ionization, exclusively addressing the atoms of the element of interest within the hot cavity ionizer tube [7]. In performing element selective laser ionization to increase the amount of the desired ions present in the source, the isobaric purity of the extracted ion beam is significantly improved [8].

The working principle of RILIS, illustrated in Figure 3, is based on stepwise resonance excitation of the valence electron of the isotope of interest. For this process, up to four pulsed laser beams are overlapped in time and position within the source, precisely tuned to the characteristic wavelengths of the isotope. With this technique, maintaining an ion beam of high purity requires detailed monitoring of the RILIS laser beam instrumentation and the precise control of key equipment to stabilize wavelength and position parameters of the laser beams.

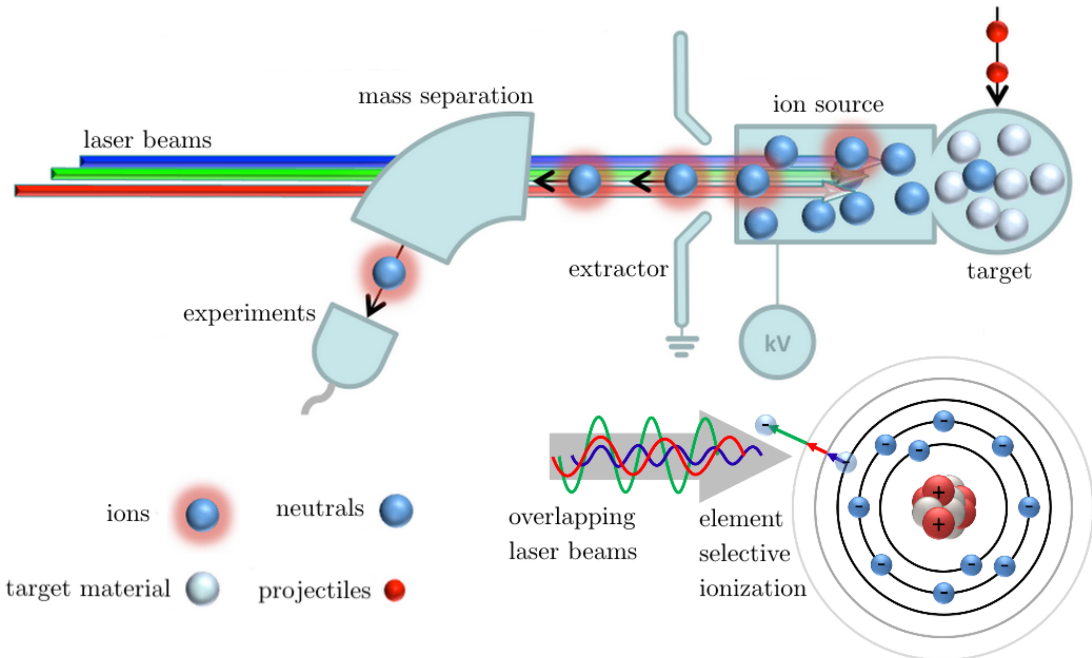

Figure 3: Illustration of the RILIS principle. (Image adopted and modified from [9])

Since the first operation of the RILIS as an experimental setup in 1991 [10], the usage of this type of ion source has steadily grown into a standard asset for the production of radioactive ion beams at ISOLDE. The increase of requested beam time in conjunction with

RILIS operation, indicated in Figure 4, has led to several modernizations and upgrades comprising the procurement of additional lasers, the update of the information technology infrastructure, the installation of sensor equipment, and the extension of the laser laboratory [11]. The work requirements for RILIS operators were extended towards conducting optical excitation scheme development in a dedicated *LAser Resonance Ionization Spectroscopy* (LARIS) laboratory [11], as well as performing ion source development at the ISOLDE off-line mass separator facility.

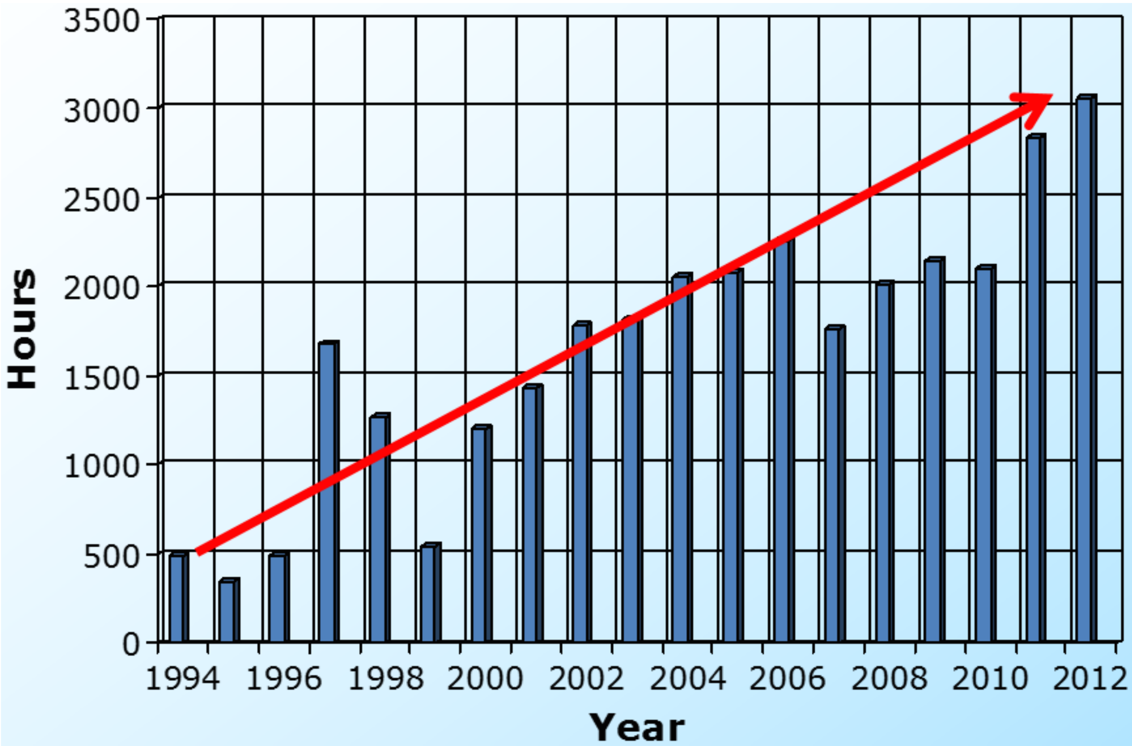

Figure 4: Increased usage of the RILIS over the last years. The availability of two complementary laser systems (Dye and Ti:Sa) has ensured the increase of RILIS beam time in 2011-2012 to 3060 h of operation in 24 separate runs with 344 RILIS operator shifts.

Due to these broadened responsibilities and the expanding array of laser equipment, the need for automation and computer control has grown significantly. Upgrades to the pump and dye laser systems [12],[13] required the installation of dedicated computers to run the equipment control software supplied with the modernized lasers. With the installation of a complementary all-solid state laser system [14] in 2011, the amount of parameters to be observed for optimal operation doubled. Figure 5 shows a schematic overview of the existing dual dye and Ti:Sa laser setup.

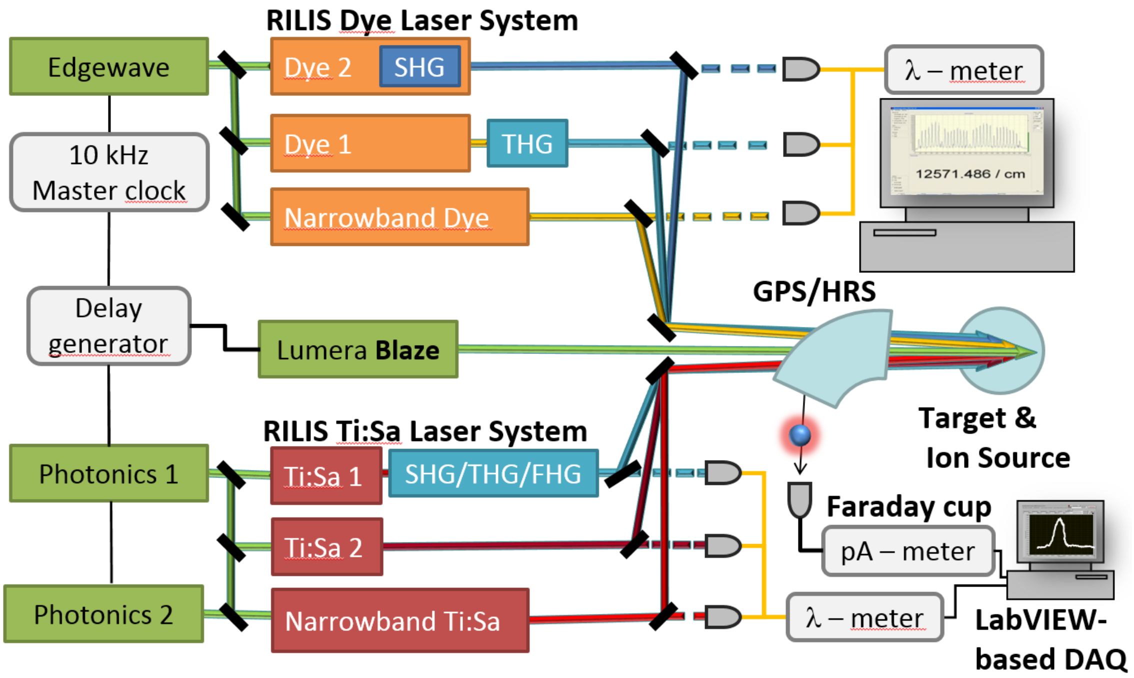

Figure 5: Schematic layout of the laser setup at RILIS. [15]

To cope with the multitude of parameters to be observed during operation, a comprehensive monitoring and control system was required to provide status information to the operators of the laser ion source. During 2011 and 2012, the foundation for a LabVIEW[3]-based software system was established in order to bundle and consolidate the process data provided by the devices within the laser laboratory. The system was first implemented as a Ti:Sa laser wavelength stabilization [16] which was subsequently extended towards a conceptual outline for an extensive monitoring and control system, described in [17]. With continued development the software has grown into the modular *RILIS Equipment Acquisition and Control Toolset* (REACT) aiming to provide *Supervisory Control and Data Acquisition* (SCADA) functionality. While most devices necessary for RILIS operation can be controlled from computers within the laser laboratory, the need for remote monitoring and control capabilities and the need to interface with setups operated by ISOLDE users has become more and more evident. This is especially true during a specific operating mode of the RILIS system known as *in-source resonance ionization laser spectroscopy*. In this mode, the RILIS is used as a powerful experimental tool to study nuclear ground state and isomer properties by high-precision scanning of an atomic

[3] *Laboratory Virtual Instrumentation Engineering Workbench* (LabVIEW) is an integrated development environment featuring a dataflow-oriented graphical programming language.

transition of the ionization scheme during a measurement of the resulting ion signature.

The primary goal of this work is to enable remote operation of the RILIS during standard operation as well as in-source laser spectroscopy experiments from a new control room outside the laser laboratory. In addition, the REACT development towards a distributed monitoring and control system is continued by implementing software utilities to support on-call operation for future RILIS operation. The requirements for a comprehensive monitoring and control system tailored to RILIS operation is outlined in the next section.

2 Motivation & Requirements

Operating the *Resonance Ionization Laser Ion Source* (RILIS) requires the dye and Ti:Sa laser preparation and the setup of optical elements within the laser laboratory according to an ionization scheme suitable for producing the ions of interest.

The RILIS principle is based on stepwise optical resonance excitation of a valence electron. For efficient excitation of atomic transitions, high-intensity nanosecond-length (5 - 30 ns) pulses of laser light are required at a repetition rate of 10 kHz. Since lifetimes of excited atomic states are also typically of the order of nanoseconds, it is necessary for the laser pulses from successive lasers to be overlapped in time. Position stabilization is required to maintain spatial overlap of up to four laser beams, which converge inside the 3 mm diameter hot ionizer cavity located about 25 m away from the laser laboratory in an inaccessible radioactive environment. The wavelengths of the tunable lasers have to be monitored and controlled to ensure the resonant excitation of each transition and to avoid and to counter drifts over operation time. Similarly, the power of the individual laser beams needs to be measured to enable optimization of the lasers and therefore to achieve optimal ionization yield. These crucial laser parameters have to be kept stable around-the-clock for each setup for up to a week at a time.

Regarding these requirements, a comprehensive set of beam diagnostic options needs to be available to the RILIS operators in the form of a flexible monitoring and control system. The development of this system should cover the following tasks:

1. The developed software and visualization tools should support the setup of the laser system within the laser laboratory.

2. Monitoring the variation in time of the laser parameters that are subject to drifts is needed for the standard mode of operation during ion beam production.

3. Control mechanisms need to be implemented to stabilize crucial laser parameters and to minimize the need for manual intervention.

4. Remote monitoring of the crucial laser parameters and automated safety mechanisms should enable on-call operation for RILIS operators.

5. Performing in-source laser spectroscopy from outside the laser laboratory requires the interconnection of devices and software to achieve remote data acquisition and laser-scan control capabilities.

This chapter provides an assessment of these tasks in the context of the operational objectives for the RILIS and discusses the potential for future software support and automation.

2.1 Operational Objectives for the Laser Ion Source

RILIS operation comprises three objectives illustrated in Figure 6: reliable ion beam provision, ion source development, and in-source laser spectroscopy. These objectives must be reached while ensuring safe operation conditions for operators and equipment.

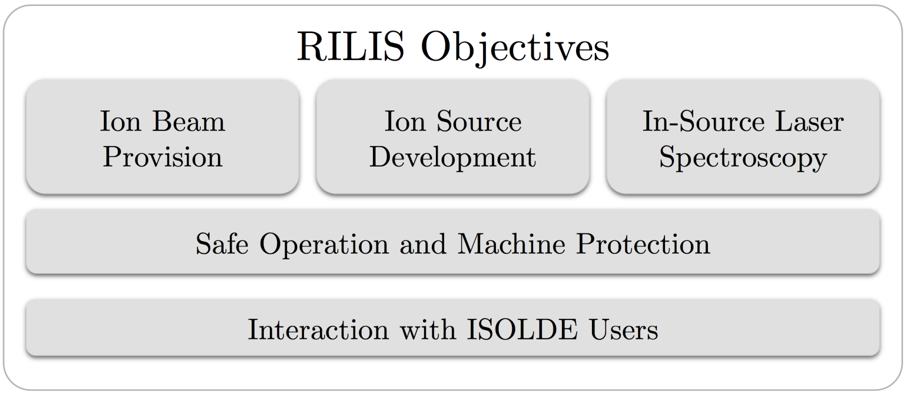

Figure 6: Block overview of the main RILIS objectives and requirements based on safe operation and machine protection.

With these objectives and requirements in mind, the continual development of the REACT system focuses on providing a comprehensive parameter overview as well as implementing an interface to access all of the RILIS process values. The operation of the laser ion source requires the observation and control of four main parameters: power, wavelength, position, and timing of the laser beams. Accessing these parameters constitutes the basis for both local and remote operation and is prominent in all use-cases for RILIS software. A tabular overview of the equipment presently in use for operating the RILIS is shown in Table 1.

2.1.1 Reliable Ion Beam Provision

The standard operation of RILIS consists of reliable ion beam provision for the ISOLDE experiment setups. The specific laser configurations and the ionization schemes employed vary for each element and every individual setup requires a certain degree of maintenance and supervision:

Equipment Type	Parameter Value	Protocol/Link	Channels
Wavemeter HighFinesse WS/6	laser wavelength	USB/dll	4
Wavemeter HighFinesse WS/7	laser wavelength/linewidth	USB/dll	8/1
Wavemeter Cluster LM-007 (Atos)	laser wavelength/pattern	USB/dll	1
Dye Lasers Sirah Credo	laser wavelength (grating)	RS-232	2
NB-dye Laser (MSS)	WL (grating & etalon)	RS-232	2
Arduino Stepper Driver	wavelength (etalon angle)	USB	2+2
Arduino Stepper Driver	laser power (waveplate)	USB	1
Powermeter Gentec TPM 300	laser power	RS-232	4
Powermeter Optometer P9801	laser power	RS-232/GPIB	8
CMOS Camera uEye (PoE)	laser beam position	Ethernet(TN)	4+1
MRC Piezo-actuated Mounts	laser beam stabilization	Analog	2
PicoMotor Mounts New Focus	laser beam position	RS-232	8
Oscilloscope Metrix	laser beam timing	USB	4
Delay Generator QComposers	laser beam triggering	USB	8
Oscilloscope Tektronix	Ti:Sa pulse timing	RS-232, USB	4
Water Chillers Termotek	water flow & level	RS-232/Dev. Srv.	4
ISOLDE Faraday Cups	ion beam current	TN, RADE/FESA	1+
PS-Booster	proton current/count	TN, RADE/FESA	2(4)+
ISOLTRAP ion detector	integrated MR-ToF counts	GPN/TN	1
Oscilloscope Lecroy	integrated ion count rate	Ethernet	1
'Windmill' alpha decay detector	alpha count rate	GPN/TN	1
Laser shutter	laser block/unblock ref.	TTL Signal	2
Pump Laser Edgewave	diode current/uptime	RS-232	1
Pump Lasers Photonics	diode current/shutter	RS-232	2
NR ionization Laser Blaze	diode current/shutter	RS-232	1

Table 1: Measurement and control equipment in permanent use for RILIS operation. (Table adopted from [17])

- The dye lasers require dye changes in intervals from 8 h to up to 1 week due to the degradation of the dye solution.

- If frequency doubled, tripled, or quadrupled laser light is required, the alignment of harmonic generation crystals has to be verified and re-tuned throughout the duration of an 8 h shift due to temperature fluctuations and internal degradation.

- Measurement campaigns probing different isotopes might require laser frequency adjustments in the range of up to $1\,\mathrm{cm}^{-1}$ of the excitation wavenumber for up to three lasers to compensate for the isotope shift of the atomic line.

- All lasers need to be occasionally blocked and unblocked in order to perform reference measurements and to compare laser on/off resonance ionization effects.

Due to their variability, these parameters require a permanent monitoring overview and a long-term trend visualization. A remotely accessible status viewing option is required for 'on-call' operation, particularly for ionization scheme setups with fewer required maintenance interventions. Hence, a web-based status indicator is beneficial for viewing process parameters on mobile devices and planning necessary interventions in advance. This permits RILIS operators to work in the 'on-call' operation mode, permitting them to allocate time to research, development and optimization tasks.

Requirements for standard operation and laser setup are

- Local monitoring of the laser parameters power, wavelength, position, and timing.
- Local control of the laser parameters power, wavelength, position, and timing.

Additional requirements for 'on-call' operation are

- Remote monitoring of the laser parameters power, wavelength and position.
- Stabilization of the laser parameters subject to drifts such as wavelength and position.
- Monitoring of the dye laser solvent parameters evaporation, flow rate, and temperature.
- Automated shutdown of the laser system if warning thresholds for dye laser solvent parameters are exceeded.
- Notification of error signals originating from the lasers and related instrumentation equipment.

2.1.2 Ion Source Development

An important factor in ensuring optimal ion beam production is the execution of ion source development, both at on-line and off-line laboratories. For this purpose, several work areas have to be addressed by RILIS operators:

On-line tests of ionization schemes first developed in the *LAser Resonance Ionization Spectroscopy* (LARIS) laboratory are performed by scanning the different ionization laser steps and recording the corresponding ion signal. This technique tests and quantifies the efficiency of ionization setups under working conditions, requiring the recording and analysis of laser beam parameters at the same time as the acquisition of ion beam information.

Developments towards additional beam purification methods involve the design, construction, and testing of more sophisticated beam instrumentation elements. One such element is the *Laser Ion Source and Trap* (LIST)[18], which requires monitoring and control programs for the power supply units of its repeller and its radio frequency quadrupole. A corresponding control software was developed in 2012 and was used to test and characterize the LIST. Another example for ion source development is the comparative performance evaluation of different ion source types such as the *Versatile Arc Discharge Ion Source* (VADIS) and the *Versatile Arc Discharge Laser Ion Source* (VADLIS) [19].

For all these tasks, a flexible set of tools is required for the RILIS operators to view and record laser parameters and ISOLDE data.

Additional requirements for development work include

- Wavelength scanning of individual lasers.
- Recording of individual laser parameters such as power and wavelength.
- Recording of ion beam current data obtained from the ISOLDE Faraday cups.

2.1.3 In-Source Laser Spectroscopy

In addition to standard operation and dedicated development work, RILIS plays an active role in conducting fundamental research experiments in collaboration with ISOLDE experiment setups. Specifically, RILIS is used for in-source resonance ionization laser spectroscopy in conjunction with specialized detectors present at ISOLDE including e.g. the 'windmill' alpha-decay spectroscopy setup or the ISOLTRAP *multi-reflectron time-of-flight* (MR-ToF) setup [20].

Due to the pulsed nature of isotope production at ISOLDE, coordination with the PSB supercycle ($\approx 30\,\mathrm{s}$ to $60\,\mathrm{s}$) and stepwise synchronized scanning of the laser frequency is required during the measurement process. The frequency of one of the tunable lasers of the RILIS, such as the narrowband Ti:Sa, is varied in steps of $0.007\,\mathrm{cm}^{-1}$ to $0.010\,\mathrm{cm}^{-1}$ per supercycle over a range of up to $0.80\,\mathrm{cm}^{-1}$ while recording a signal corresponding to the ion beam intensity of the isotope of interest. Throughout this process, all other laser related parameters: power, position, and timing, are essential to be constant to ensure stable measurement conditions. Corresponding stabilization programs used for laser spectroscopy have to support the RILIS operators by automating repetitive equipment control processes.

In-source laser spectroscopy data recording also relies on the coordination with detector setups present at ISOLDE which each have their own unique equipment control and measurement systems. Therefore, the RILIS data acquisition system has to be adaptable to the collaborating experimental setups in both hardware and software.

Additional requirements for in-source laser spectroscopy experiments are

- Monitoring of the spectral structure of the narrow-linewidth ionization laser.
- Simultaneous recording of all available laser parameters.
- Recording of ion beam current data obtained from the ISOLDE Faraday cups.
- Synchronization and coordination with ISOLDE experiment setups.
- Recording of the 'windmill' alpha-decay count rate and spectra.
- Recording of the ISOLTRAP MR-ToF count rate.
- Recording of proton current data obtained from the Proton Synchrotron Booster.
- Stabilization of the crucial laser parameters power, wavelength, position, and timing during the laser scan process.

2.2 Safe Operation and Machine Protection

Operating the laser ion source involves risks introduced through machine-related hazard factors which necessitate safety measures. Thus, a fundamental task for RILIS operators is to ensure safe operation of the laser installation.

The presence of four water-cooled 60 W to 100 W class 4 Nd:YAG pump lasers in conjunction with dye laser operation requiring ethanol as a flammable dye solvent creates potential risks for the operators, as well as for the machines. While some risks such as exposure to laser radiation or electrical hazards are minimized by passive mechanisms (i.e. proper shielding and grounding), other sources of potential faults must be actively monitored remotely. Among these are critical parameters such as the dye flow and the ethanol concentration in the air.

In the event of a dye leak, the ethanol which is used as a solvent for the dye, will evaporate and may create a combustible mixture, representing a potential fire hazard. Active automated monitoring of the ethanol content in the air near critical points within the laser enclosure and on the laser table provides an early warning mechanism for the operators by sending text messages to the designated operator mobile phone. In the event of a severe dye leak, registered by sensors in the different lasers, the automated system is capable of stopping the pump lasers through an interlock signal and thus to prevent potential dye ignition.

Failure of a dye circulator during the irradiation of the dye cell may cause irreparable damage due to the lack of cooling. This can be prevented by constantly monitoring the flow rate of the dye and enabling safety shutters to actively block the pump laser beams. Additional non-critical monitoring parameters, such as the dye temperature, help to estimate the condition of the dye, as well as the overall stability of the laser system due to temperature fluctuations. Constant observation of these parameters requires the installation of an autonomously operable machine protection system capable of shutting down the RILIS system in the event of a severe problem.

The health and safety of the operators is of primary concern besides machine protection and monitoring of critical parameters. Due to its location above the separator magnets in the ISOLDE hall and with a large array of installed equipment, the laser laboratory represents an area with increased levels of radiation, potentially hazardous chemicals, and noise. As a requirement for improved working conditions, the RILIS equipment necessary for long-term operation during a physics measurement campaign should be supervised remotely from outside the laser laboratory, in a separate control room, located in a non-radiation supervised or controlled area.

In the years 2013 to 2015, CERN facilities underwent a general maintenance and upgrade phase during the *Long Shutdown 1* (LS1). During this phase, a new office building[4] was constructed outside of the ISOLDE experimental hall. The new building houses off-site laboratories in the lower floor and control rooms and offices in the upper floor. Figure 7 shows a photo of a new *RILIS control room* (508 1-015) in the beginning of April 2015 prior to its commissioning. This new area is designated as the 'operations room' to house workstations enabling the remote monitoring and control of RILIS equipment.

[4]The new building 508 is located on the northwest side of the ISOLDE hall building 170.

Figure 7: 360° panoramic photo of the new RILIS control room in building 508 prior to its commissioning.

2.3 Interaction With ISOLDE Users

Both the operational objectives as well as the machine protection aspects require well established communication between RILIS operators and the ISOLDE users. In order to provide a comprehensive status overview, relevant aspects to be communicated range from the simple 'on/off' operational state of the lasers to specific measurement-related information such as power levels and wavelength settings. Users should be provided with well-defined interaction capabilities ranging from blocking and unblocking laser beams remotely up to the remote control of frequency scanning individual lasers. An active data exchange is pursued in providing interfaces to communication protocols and programming languages used by ISOLDE experiment setups. This ensures an active collaboration in software development and in the implementation of experiment requirements.

3 Conceptual Design

This chapter surveys the basic software building blocks available to approach the task of extending the REACT software collection towards a distributed monitoring and control system. Available software environments at CERN for creating distributed monitoring and control systems are investigated and subsequently adapted to meet the specific requirements for RILIS operation.

3.1 Software and Development Environments at CERN

There are a wide variety of software distributions, programming languages, and development environments in use at CERN to address areas such as *Human-Computer-Interaction* (HCI), *Data Acquisition* (DAQ), and equipment control. Experimental setups often require both standardized solutions as well as specifically customized control software to meet the needs for fundamental research. The following selection highlights specific task domains:

- Java is an established programming language used to implement graphical user interfaces, visualizations, and data distribution middleware at CERN. [21]
- Python provides a multitude of included libraries to solve tasks ranging from implementing specific scripting solutions to creating complex measurement applications. [22], [23]
- The Root data analysis framework provides libraries to investigate and display the complex amount of data acquired by the *Large Hadron Collider* (LHC) and other experiments. [24]
- Programming languages such as C and C++ are mostly used for implementing low-level system software which directly communicates with hardware and provides raw data. [25]
- The LabVIEW development environment is used to implement the low-level control system of the LHC collimators [26] and to implement measurement and test systems by the CERN EN-ICE-MTA[5] section. [27]

[5] Engineering Department - Industrial Controls & Engineering - Measurement Test Analysis

The requirements for RILIS operation include both substantial hardware interaction and the need to quickly adapt to varying setup configurations. For this reason, the REACT framework was implemented using the *Integrated Development Environment* (IDE) LabVIEW (short for *Laboratory Virtual Instrumentation Engineering Workbench*) by the company *National Instruments* (NI).

The advantages of using LabVIEW lie in the availability of hardware communication interfaces and in the fact that programs with *Graphical User Interfaces* (GUIs) can be developed in collaboration with RILIS operators as domain experts for the laser installation. LabVIEW is a graphical programming language that focuses on data flow and features a visual approach to programming by linking pre-programmed functional nodes through colour-coded wires representing specific data types. A LabVIEW program is called *Virtual Instrument* (VI) and consists of a front panel (the GUI) and a block diagram (the graphical source code). The inclusion of the GUI in each program as well as the data-flow oriented programming allows for an intuitive approach to generating small, application-specific software tools. Making use of the graphical programming method enables the physicists operating the RILIS to extend the system according to changing requirements and demands. In order to address more complex programming tasks, there are a variety of design patterns [28], [29] available that make use of the inherent parallel execution within LabVIEW. It is furthermore possible to include source code of other programming languages such as C/C++ or Matlab on the block diagram of LabVIEW VIs, allowing the code reuse of externally implemented algorithms.

3.2 Distributed Monitoring and Control Systems

Monitoring and control tasks in distributed information technology environments usually fall into the domain of *Supervisory Control and Data Acquisition* (SCADA) systems. As an example, the process control of industrial environments such as power plants and factories must be coordinated and made accessible to human operators.

3.3 Available Frameworks and Technologies

The LabVIEW development environment provides several established modules and technologies that facilitate the implementation of complex industrial applications. One such technology is the NI *Shared Variable Engine* (SVE), which provides a standardized communication protocol for simplified and fast data exchange over Ethernet. [30] The protocol is furthermore compliant with established industrial solutions such as *Open Platform Communications* (OPC) servers and thus opens the possibility of integrating heterogeneous systems.

The shared variable technology is supplemented and extended by the *Datalogging and Supervisory Control* (DSC) module [31]. This commercial module extends the LabVIEW programming environment by providing comprehensive programmatic control over shared variable management and offers the recording of process variables as well as defining warning and alarm values. Figure 8 illustrates the network shared variable communication process implemented in LabVIEW.

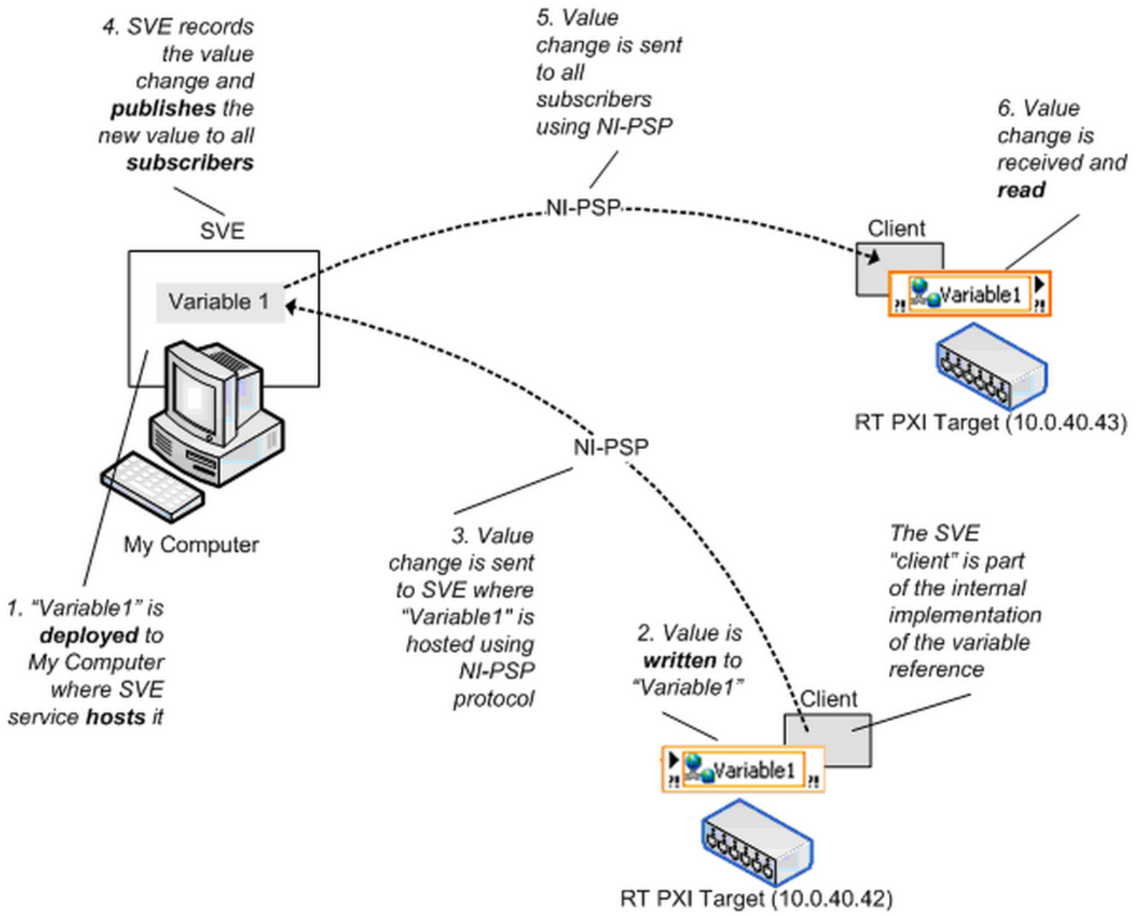

Figure 8: Illustration of the *Network Shared Variable* communication in LabVIEW. [30]

The shared variable engine runs as a service on a host computer. Within this engine, individual processes can be defined either manually or by deploying a library containing network shared variables. LabVIEW programs running on the computers within the network can subscribe to the shared variable host using the proprietary *National Instruments*

Publish and Subscribe Protocol (NI-PSP). When a client is changing the value of a shared variable, all connected subscribers are notified about the data change, transferring the new data within 10 ms time or when more than 8 kB worth of data has been modified. The major advantage of using the shared variable mechanism for data exchange is that no low-level network code needs to be implemented to handle the communication procedure.

The communication with other monitoring and control systems present at CERN is enabled through the use of external libraries and software frameworks. Using the *Rapid Application Development Environment* (RADE) [32], [33] developed by the CERN LabVIEW support group, it is possible to interface directly with the CERN control infrastructure. This infrastructure consists of several middleware software layers and architecture components to provide access to accelerator equipment and to perform service functions such as data logging. The *Front End Software Architecture* (FESA), implemented in C++ and Java, is used to communicate with front-end computers and physical devices [34]. The *Controls Middleware* (CMW) represents an interface to monitoring, diagnostics and service functions. In using corresponding RADE functions, LabVIEW programs can interface to these domains and extract useful data for RILIS operation.

3.4 Adaptation to the RILIS Setup

There are numerous software technologies and SCADA frameworks in existence which share a conceptual layered approach. These abstraction layers provide a software engineering and design transition from low-level hardware to top-level GUI software. A conceptual software layer schematic representing the REACT concept is shown in Figure 9.

Most of the framework components are suitable and designed for large-scale industrial implementation, likely spanning multiple facilities. Therefore, the application for RILIS requires the adaptation of the basic concepts and standards of distribution and modularity on a reduced scale. This adaptation leaves room for possible extensions and ensures compatibility with existing frameworks.

- The bottom layer (yellow) consists of hardware devices related to the principal RILIS process values of wavelength, power, position, and timing, as well as other environmental parameters. The implementation of this layer mainly consists of cabling at the lowest level and setting up device parameters such as calibration values and channel settings within the devices.

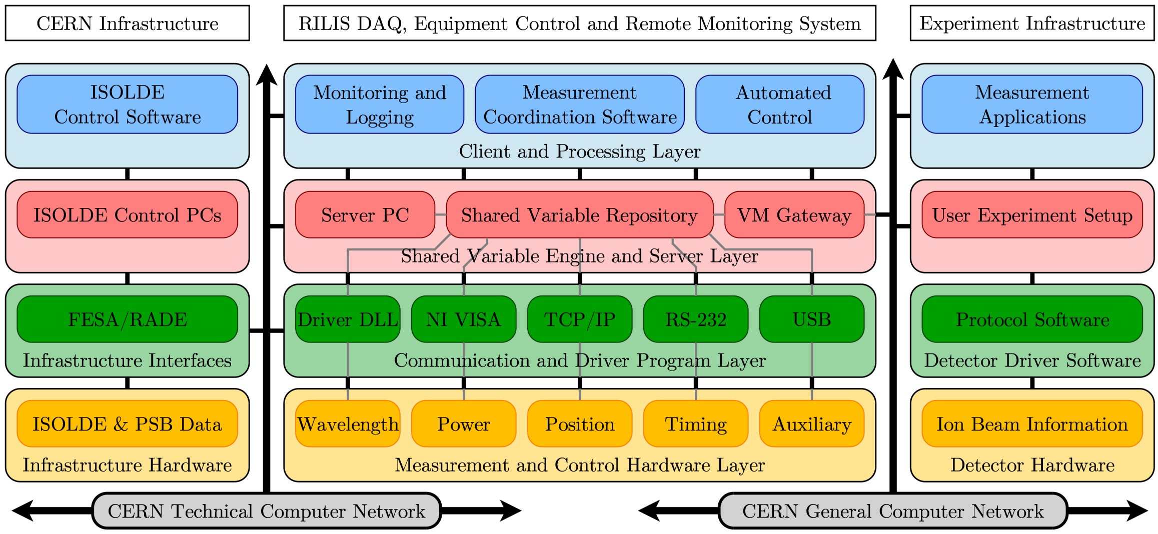

Figure 9: Layer schema of the REACT concept. The depicted layers cover four principle domains (from bottom to top): hardware, back-end software, middleware, and front-end software. These domains span left to right from the closed CERN *Technical Network* (TN) infrastructure over RILIS equipment to the *General Purpose Network* (GPN) experiment setups.

- The next layer (green) above represents driver software interacting directly with the equipment. The modular driver programs make use of software provided by the manufacturers, as well as custom developed read-out programs to communicate with hardware and access specific functions. The infrastructural requirement of communicating with the ISOLDE controls framework can be met within this layer.

- The third layer (red) comprises the middleware and interface layer, implemented through the use of LabVIEW shared variables. The process values acquired by the device drivers from the previous layer are hosted in shared variable processes on the computer that connects to the device. Subsequent VIs can subscribe to this data repository and independently make use of the variables. This layer also provides optional data recording, alarming, and security capabilities and offers extended *Machine-to-Machine* (M2M) connectivity through the OPC compatible implementation of LabVIEW shared variables. The infrastructural requirement of communicating with the experimental setups can be met here.

- The top layer (blue) consists of interactive programs that are specifically developed to address the RILIS operational requirements. The main categories here cover monitoring of laser parameters, recording of measurements, configuration management and performing automated control tasks. GUIs provide the operator with a visualization of process values such as long-term trend-line displays, as well as data logging and control applications. Other custom developed 'Service-VIs' make use of the pool of shared variables by implementing automation functions such as stabilization or data acquisition routines.

The key concept within the REACT framework is to provide flexibility through modularization and data distribution. Each program component should be developed to provide high cohesion and loose coupling as general software engineering principles. High cohesion refers to the grouping of similar functionalities and to one component performing a single specified function. Loose coupling aspires to minimize the interconnection between program components and reduce their degree of dependencies [35]. Adhering to these principles facilitates interchangeability of components and simplifies parallel development of individual programs. Device drivers for new equipment as well as automation routines can be developed independently by the RILIS operators and the software framework can be adapted to new constraints or requirements.

4 Implementation

The current implementation state of low-level REACT hardware and software components is documented within this chapter to provide an overview of the hardware and driver program layers and their link to the network shared variables. Several of the programs described in the following text were developed as proof-of-concept and prototype versions to solve specific project requirements during previous activities and related works:

- A Ti:Sa laser wavelength stabilization program was developed in 2011 to compensate wavelength drifts due to temperature fluctuations within the RILIS laser laboratory. [16]
- The data acquisition software for RILIS was reworked in 2014 to incorporate flexible selection of data sources and to improve the communication of live-data to collaborating experiments. [36].

The REACT software collection has emerged out of these projects and represents now a comprehensive set of applications to support RILIS operation. An overview of these utility programs and routines which are organized in independently maintainable LabVIEW projects[6] is provided in Table 2.

The descriptions for the projects which have been implemented before the start time of the present thesis work in April 2015 are marked with the symbol ♣. Since these projects form part of the distributed monitoring and control system for the RILIS installation, their descriptions are provided for completeness as complementary documentation in this presentation of the REACT concept. Additionally, suggestions and recommendations for further development and refactoring are given to address the extension of the software framework. Projects and program components that have been implemented or modified specifically during the scheduled time of this thesis are marked with the symbol ★. Additional program components were developed by the RILIS operators by making use of the shared variable infrastructure that was established for the aforementioned projects. These user-developed programs are marked with the symbol ■, and they exemplify one of the non-functional goals of the REACT concept: To enable the extension of the software collection on demand through the expertise of RILIS operators to better meet operative requirements.

[6] All projects indicated in the table can be found within the RILIS network folder under `\LabVIEWprograms \Projects and Source code\<project name>`

Monitoring Driver Programs
Camera Driver (Position Monitoring) ♣ ★
HighFinesse WSx wavemeter Readout ♣
RILIS Atos LM007 wavemeter Software ♣ ■
Gentec TPM300 Powermeter Readout ★
RILIS MultiPowermeter Readout ■
LeCroy WaveRunner 104Xi Scope Readout ■
Keithley 6487 PicoAmMeter Readout ★
ISOLDE Device Readout ♣
PSB Telegram Readout ♣
PSB PPP and PC Readout ♣
DAQ Card in PXI ■
RMPS Communicator ★
Control Driver Programs
Picomotor Driver (Position Control) ♣
Arduino XY Stepper Driver ♣ ★
Credo Laser Control ★
Motorized Waveplate ★
Quantum Composers Delay Generator Driver ■ ★
Top-Level Utilities
LaserIonSourceMAPper ■
RILIS eLogbook Posting Tool ♣
RILIS Status Viewer ■ ★
Shared Variable Viewer ★
Shared Variable Logger ★
TiSa Delay Compensator ■ ★
Power Stabilization ★
VISTARS Status Control ♣

Table 2: Overview table of LabVIEW programs currently available to RILIS operators.

4.1 Modular Device Drivers

As a base for all hardware device interactions, a set of modular device driver programs has been developed. These drivers and their hardware counterparts are represented by the two lower layers of the REACT concept diagram and are highlighted in Figure 10 below.

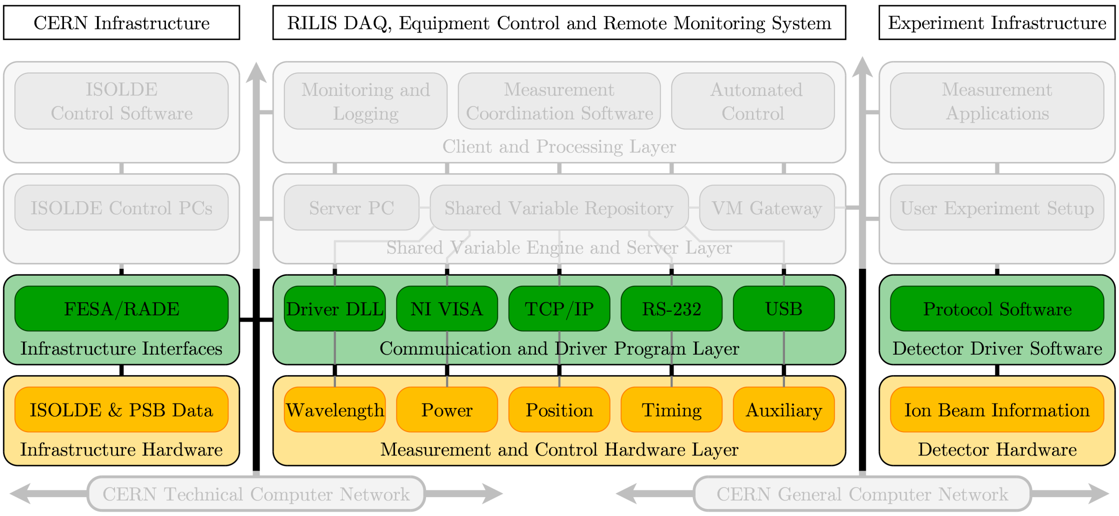

Figure 10: View of the hardware and device driver layer of the REACT concept diagram. Each device responsible for monitoring or controlling crucial laser parameters such as wavelength, position, power and timing is controlled by a dedicated LabVIEW device driver program.

To cope with the quantity and diversity of hardware equipment required for RILIS operation, a modular approach was chosen: Simple read-out and control programs are created to provide specific access to a subset of possible read-out and control values for a device. This way, new features can be implemented on demand or the driver programs can be replaced or refined with minimal impact on the overall framework. To access advanced features or low-level configuration options, the original software supplied by the manufacturers can be started locally on the computer controlling that device.

The implementation of the device driver programs relies on the use of communication libraries such as *Dynamic Link Libraries*[7] (.dll) files, string-based communication protocols as used with the RS-232 interface, or pre-programmed LabVIEW nodes provided by the manufacturer of the equipment. The only purpose of the device driver programs is

[7]Pre-compiled library files to allow external and shared function calls during run-time of a program.

to publish the extracted values from the hardware devices as shared variables. These can then be accessed by top-level programs intended for user interaction.

4.2 Monitoring Driver Programs

The monitoring driver programs extract and publish laser parameters and do not directly perform any control functions. The programs within this category are required throughout RILIS operation and are to be launched during the laser setup phase. They continue to run in the background, publishing the acquired values to shared variables without requiring user interaction.

4.2.1 Camera Driver (Position Monitoring) ♣ ★

Laser beam position reference: For RILIS operation, up to four laser beams are sent into the 3 mm aperture of the ion source. Over a path length of approximately 25 m they converge and overlap inside the hot ionization cavity. A wedged quartz reference plate is positioned to intercept the laser beams at the half-way point along their path.The laser beams are transmitted though this plate with negligible losses or beam steering but Fresnel reflections from the two quartz/air interfaces of the wedge produce a pair of 4 % reference beams for each laser beam. These are directed back into the RILIS laser laboratory. Since the total path lengths of the reference beams matches those of the main beams at the position of the ion source, these reference beams are an effective means of assessing and optimizing the spatial and temporal overlap, focusing and transmitted power during the setup phase for RILIS operation. They are then used to define these reference conditions for to be maintained during an experiment.

Laser beam path designations: Each laser beam path is designated with a colour name: Red, Blue, Yellow, and Green, corresponding to the coloured buttons of the gamepad controller used for the beam position control program described in 4.3.1. If applicable for the scheme, the green beam path transports the green 532 nm non-resonant ionization laser while the blue beam path is preferably used for laser beams in the UV range. This designation serves as a reference during setup and operation and is used to identify elements for both laser beam observation and laser beam steering, described later in this section. This concept simplifies troubleshooting procedures in complex setups and was introduced during the *GPS Launch And ReferencE* (GLARE) upgrade: a re-modelling of the launch mirror and reference observation area carried out in 2014 [15].

Digital camera hardware setup: Four *Power-over-Ethernet* (PoE) *Internet Protocol* (IP) digital cameras[8] are placed on the optical table of the reference beam observation area within RILIS. The reflections of the overlapped laser beams are sent back to this reference setup where they are separated using diffraction gratings and are guided through prisms to enable individual observation of each beam. These individual beam spots are directed either directly or through neutral-density filters onto the rectangular CMOS[9] sensor area of the digital cameras which measure 6.784 mm by 5.427 mm and act as a 'virtual ion source' reference for the laser beam position.

Reference image information: The image produced by the digital cameras provides information about the position of the laser beam, visualizes the laser beam shape, and gives an indication of the relative laser beam intensity. The ability to observe this live camera signal and manipulate camera exposure settings is essential for the RILIS operators during the setup phase of the lasers. An example screenshot of the front panel of the beam observation program is shown in Figure 11. In the pictured setup, the beam paths blue (top right), yellow (bottom left) and green (bottom right) are used. The visible 'heat-map' pixel colouration of the images is derived from the original black and white image where high-intensity white pixel values are mapped to the red colour and low-intensity black pixel values are mapped to the blue colour.

LabVIEW program structure: The read-out program for the digital cameras consists of seven loops running in parallel, illustrated in Figure 12. Four of these loops communicate with the four corresponding IP cameras. Three additional loops are dedicated to process user interactions occurring on the front panel, to communicate with the position control interface program (see 4.3.1), and to publish a screenshot of the most recent front panel image to the RILIS status website[10] in regular intervals. In the current implementation, the core functionality of the camera readout is performed through *invoke nodes*[11] on the block diagram which access a *.net* object reference representing a wrapper around a shared library (uEyeDotNet.dll) provided with the driver software installation.

[8] Model uEye UI-5240CP-M-GL by IDS Imaging Development Systems GmbH
[9] Complementary metal-oxide-semiconductor
[10] `http://riliselements.web.cern.ch/riliselements/lasers/`
[11] Invoke nodes provide access to functions of classes which make up the underlying implementation of LabVIEW.

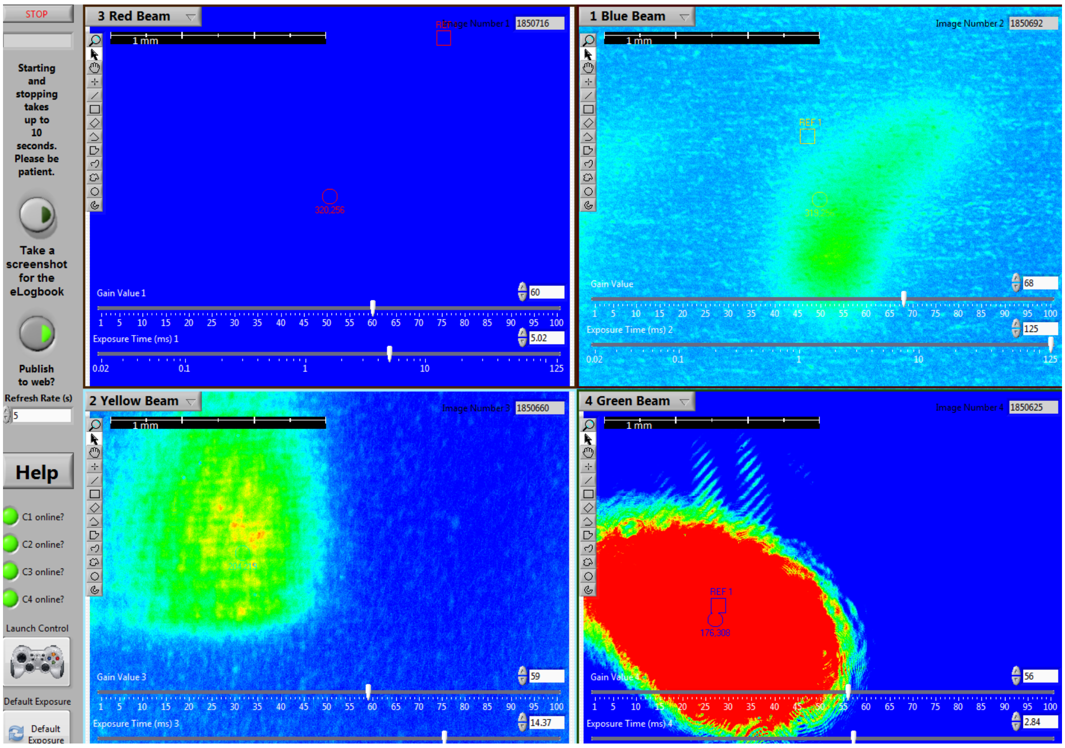

Figure 11: Screenshot of the front panel of the laser beam observation program displaying three active laser beams in a 'heat-map' colour coded representation.

Implementation issues: Continued development, long-term usage, and testing of the program in 2014 revealed the following drawbacks of the implementation state at that time:

- **Memory leaks:** Accessing properties of the camera through *property nodes*[12] creates new references in memory which have to be closed after calling the associated function. This has been addressed in 2014 by using the *LabVIEW Desktop Execution Trace Toolkit* [37] to identify memory leaks and refactoring the application to use more modular SubVIs and to explicitly close all references right after use.

- **Program lock-ups:** It was observed during operation that the front panel of the laser beam position display program occasionally became unresponsive for arbitrary durations. The problem has been narrowed down to the publication loop of the front panel image at an interval of 5 s. Since all seven loops are running within the same VI, which also displays the front panel itself, they are tied together by

[12] Property nodes provide access to properties of classes which make up the underlying implementation of LabVIEW.

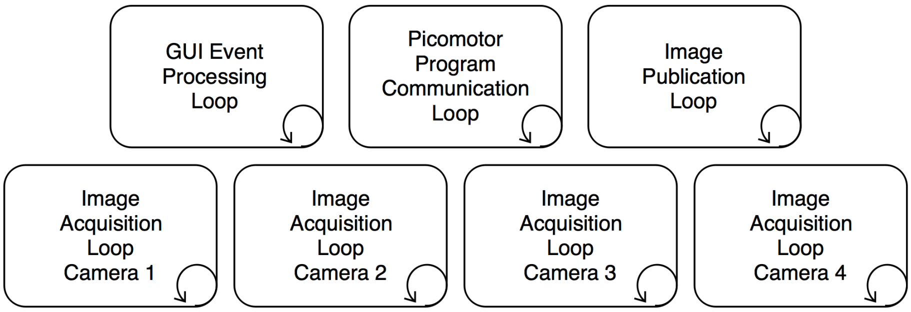

Figure 12: Schematic overview of the structure of the laser beam position monitoring program.

the LabVIEW run-time engine to run within the *Graphical User Interface* (GUI) thread. This undermines the inherent parallelization of LabVIEW and the loops are not running within their own threads as intended. As a consequence, a loop that stalls causes the other loops to also suspend their execution until the blocking loop is exited. In this case, the publication loop locks-up related to the writing of the image file to the webserver resource directory, potentially caused by automated backup routines or network traffic issues.

- **Program maintenance:** The first program version relied on code duplication of the four camera read-out loops. The principle functionality of the raw image acquisition routine was implemented utilizing dedicated SubVIs provided by the manufacturer and offered no image processing options. The inclusion of feature requests such as calculating the centroid of the image or manipulating the exposure value at run-time is difficult to achieve efficiently if each loop has to be addressed individually. A future implementation should encapsulate the read-out loops into self contained SubVIs which can then be called with the camera addresses and individual settings as parameters.

- **Remote monitoring:** The beam position monitoring application is to be run on the computer to which the cameras are connected. Currently this is the RILIS-PXI system in the laser laboratory. Monitoring the camera image on a remote computer requires the image data to be transferred over the network. However, the cameras provide a 1280 by 1024 pixel raw-data image at 20 frames per second which causes a network load of 20 % to 25 % of a gigabit ethernet connection. Thus, the inclusion of image processing and compression routines is required for future implementations.

Addressing arbitrary program lock-ups: The issue of the beam position monitoring program locking up due to the publication of the front panel as a screen shot[13] has been addressed by first saving a local copy of the image and then using a separate, independently running executable to copy the image to the webserver resource directory. This ensures that the beam position display remains responsive and can be viewed locally by the RILIS operators present in the laser laboratory. However, the original reason for the file copy delay needs to be investigated in more detail e.g. by checking whether the overwriting of the front panel image at an interval of 5 s causes a backlog due to the RILIS webspace settings concerning file backups. An alternative solution to this problem could use *Remote Front Panels*[39]. However, this would require additional configuration work concerning the compatibility between the LabVIEW remote panel server running locally and the CERN webserver hosting the RILIS website.

Pixel grayscale value sum as laser power indicator: The extraction of the sum of the 8-bit grayscale value for each pixel of the individual images was implemented into the image acquisition routine to provide an additional beam intensity read-out. This has become a convenient and reliable means of long-term monitoring the relative laser power in the ion source without requiring the setup of dedicated extra hardware for power measurements. This has been used in combination with intensity read-outs obtained from position sensitive detectors (see section 4.2.10) and power meter readouts (see section 4.2.4) to record and visualize long-term laser beam power trends.

Development towards the modular REACT concept: In order to address the program maintenance issues and to improve remote monitoring capabilities, the camera read-out program was refactored to use a single read-out loop which is instantiated individually for each camera and to separate the image acquisition from the image display. This will facilitate future maintenance but requires an increased amount of internal data communication: The acquired raw image is published as a shared variable which can be read locally by a viewer program and, in addition, remotely on another PC within the technical network. The latter option will potentially increase network traffic and should be addressed in future implementations by reducing the image size and adding image compression and encoding options. The needed image compression and scaling program can be implemented as a separate module which then publishes the processed image as a

[13] This method is described by National Instruments in [38] as a way of simple front panel monitoring.

shared variable or as an encoded video data stream. A corresponding viewer program has to be implemented or available media player software solutions such as *VideoLAN Client* (VLC) could be used to observe the transferred image or video data.

4.2.2 HighFinesse WSx Wavemeter Readout ♣

Wavemeter hardware setup: RILIS is currently equipped with two different models of *HighFinesse* wavelength meters[14]. Each wavemeter is connected to an optical fiber switcher device which enables the measurement of multiple laser wavelengths in rapid succession (multiplexing), depending on the set exposure time. The current setup makes use of a 4-channel switcher for the WS/6 wavemeter. This wavemeter is connected to the computer `RILIS-SCREEN-1` and is used during the Ti:Sa alignment and setup process. Specific details concerning the Ti:Sa laser setup can be found in [10]. An 8-channel switcher is used for the WS/7 wavemeter connected to the computer `RILIS-SERVER` in order to monitor multiple laser beams simultaneously during operation. A frequency stabilized helium:neon (He-Ne) laser is coupled into the respective last channel of the switchers to allow for a reference measurement of the wavemeters.

LabVIEW program structure: To extract measurement data, the *HighFinesse* wavemeters use the technique of shared memory access through function calls to a dynamic link library file (`wlmData.dll`) provided by the manufacturer. This file is unique for each wavemeter and needs to be located in the Windows *System32* (*SysWOW64* for 64 bit systems) directory. For this reason and due to the computational load caused by processing measurement data from the sensor electronics, each wavemeter is connected to a dedicated computer.

The wavemeter read-out program consists of a single do-while loop, which executes calls to `wlmData.dll` functions in regular intervals of $\approx 20\,\text{ms}$ to acquire wavelength measurement values and exposure information. This requires the original software supplied by the manufacturer to be running in the background to handle the sensor electronics read-out, USB communication as well as wavelength and linewidth calculations. Figure 13 shows a detail view of the LabVIEW block diagram which is responsible for extracting the wavelength measurement.

[14]Models and configuration options[40]:
WS/6 D L MC (Diffraction Grating Hybrid (D), Linewidth Measurement (L), Multi-Channel (MC)
WS/7 L MC UV t (Linewidth Measurement (L), Multi-Channel (MC), UV Measurement Range (UV))

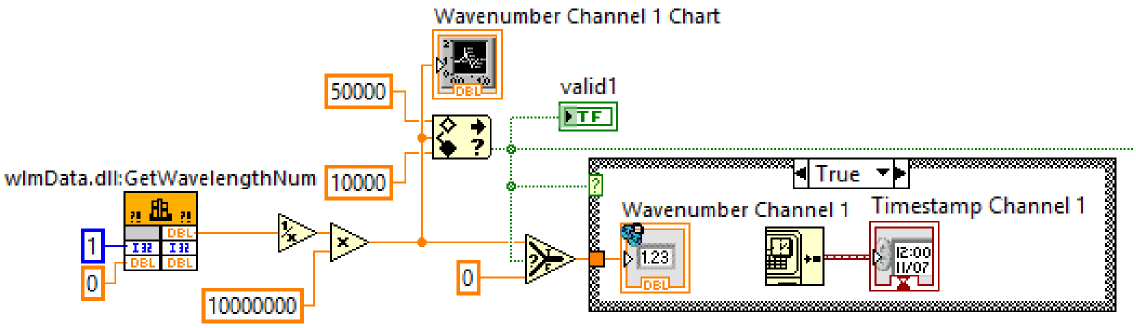

Figure 13: Block diagram clipping responsible for reading out the wavenumber value from the wavemeter. This clipping is presently duplicated for each channel to be read.

On the left, the call to the function named `GetWavelengthNum` is executed taking the integer parameter '1' (shown in blue) as the channel to be read. Next in data flow, the acquired wavelength value is converted to the corresponding wavenumber[15] value using the expression $\lambda^{-1} \cdot 10^7$ (λ in nm). The resulting value is checked for validity and displayed on the *Wavenumber Channel 1 Chart* indicator. Values between the upper limit of 50000 cm^{-1} and 10000 cm^{-1} are considered valid and are published to a corresponding shared variable. Values outside this range are considered unphysical as the output range of the RILIS lasers lies between 200 nm and 1000 nm. Faulty values may occasionally occur due to read-out errors e.g. when the wavemeter sensor is underexposed.

The LabVIEW *Call Library Function* block diagram node is configured using the dialog window shown in Figure 14. On the leftmost tab labeled 'Function', the desired `.dll` file is selected and parsed, subsequently showing all callable function names. The selected function, in this case `GetWavelengthNumber`, can then be configured using the pictured 'Parameters' tab. More details are given in the programmer's manual of the wavemeter which denotes all callable function prototypes, their parameters and their data types [41].

Future implementation concept: The current version of the wavemeter read-out program can be used for both types of *HighFinesse* wavemeters, since the configured function calls are identical. However, the highest priority for future implementation work is the extension of the wavemeter read-out program to acquire eight channels instead of currently four, as the optical fiber switcher hardware was upgraded to allow for the

[15] In optical spectroscopy, the *wavenumber* unit cm^{-1} (inverse cm or Kayser), is preferred as it is proportional to the photon energy.

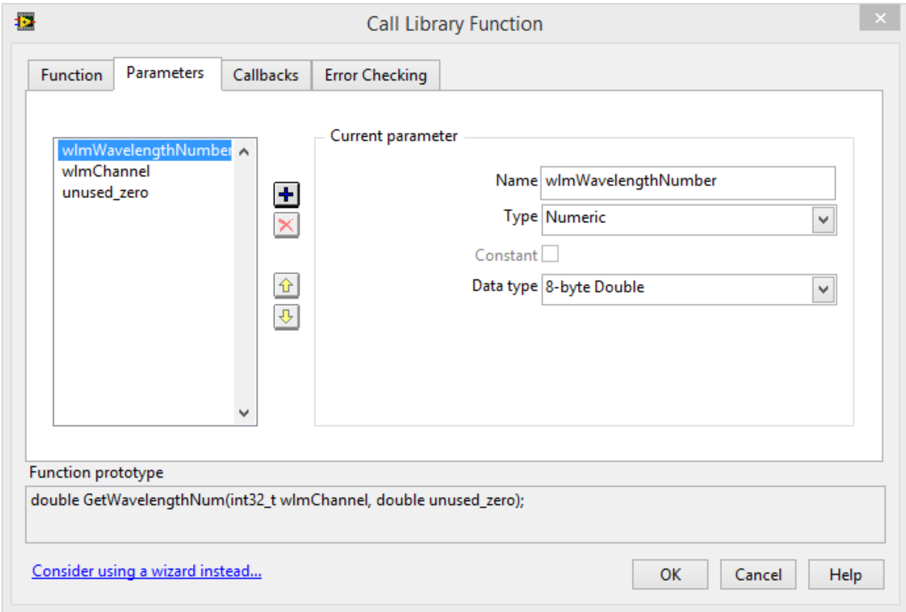

Figure 14: Screenshot of the configuration dialog for the *Call Library Function* node.

connection of eight input fibers. For this purpose, the program structure should be improved from using a single-loop performing parallel `.dll` function calls towards a state machine based implementation. This will simplify future extensions and increase the maintainability of the program by utilizing SubVI calls within the program execution states. As another task, the shared variable deployment implementation needs to be revised to match the currently connected wavemeter type. This can be accomplished by calling the `wlmdata.dll` library function `GetWLMVersion` to identify the connected wavemeter type, version, revision, and software. By programmatically identifying the type of the wavemeter, the deployment path for the shared variables can be constructed accordingly and only the corresponding shared variables can be deployed.

4.2.3 Gentec TPM300 Powermeter Readout ★

Flexible laser beam power measurements: RILIS is equipped with five portable power meters of the type *Gentec TPM300* with exchangeable measurement heads to cover power measurements from 10 mW up to 100 W. These power meters are used during the RILIS setup phase to acquire full-power measurements of the laser beams when tuning optical elements to optimize the output power. For the operation phase of RILIS, the power meters can be moved on the laser table to a convenient location for the measurements at pick-off and beam-splitting points to establish specific long-term read-outs. In such a measurement, the residual fundamental dye laser power was measured after the harmonics generation unit to enable a live assessment of the dye degradation and the frequency conversion efficiency.

LabVIEW program structure: The structure of the *Gentec* power meter device driver program represents the bare minimum necessary for continuously reading values from a device: A single do-while loop, shown in the screenshot in Figure 15, implements the basic pattern of initialization, communication, and shutdown for interacting with hardware.

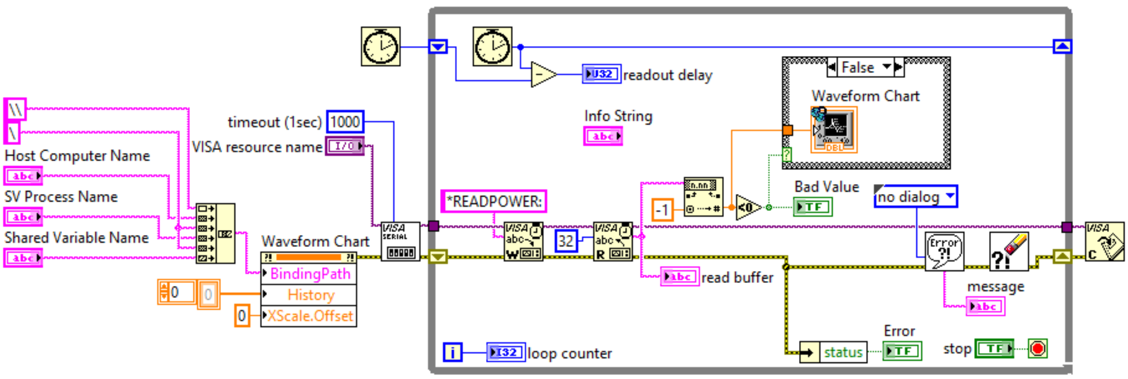

Figure 15: Screenshot of the block diagram of the *Gentec* power meter program.

On the left side of the block diagram, the shared variable data binding path is configured which enables a *Waveform Chart* front panel indicator showing a trend-line view of the acquired values to publish its latest value to the corresponding shared variable. Next, a configuration node of the *Virtual Instrument Software Architecture* (VISA) [42] library, which is provided with LabVIEW, is used to configure the communication via the serial data transmission RS-232 standard. The VISA architecture represents a standardized programming interface for communication protocols and provides pre-programmed nodes to send and receive data strings. Within the loop, values are requested from the power meter by sending the string `*READPOWER:` and reading up to 32 bytes in response. The received string is converted into a double value and subsequently displayed on a pre-programmed waveform chart if the conversion was successful. If the conversion was not successful, a default double value of -1 is returned, indicating a bad value which is not published. Potential errors, such as communication time-outs, that may occur during the loop iteration are only displayed and then cleared to allow for the program to run and recover without requiring any user interaction. Pressing the stop button on the front panel causes the loop to stop and the communication interface is shut down by the VISA close node on the far right of the block diagram.

4.2.4 RILIS MultiPowermeter Readout ■

Long-term laser beam power measurements: An 8-channel multi power meter[16] is available in the laser laboratory to complement the flexible laser power measurements of the full laser beam power using the *Gentec TPM300* power meters. The multi power meter features eight analog input channels to which photodiode-based power meter heads can be connected. These power meter heads are suitable for measuring low laser powers of up to 200 mW and are used to acquire long-term reference measurements of low power beam reflections or leakage beams occurring inevitably at optical surfaces. These reference measurements provide a low-invasive means of monitoring the laser beam power over long periods of time.

LabVIEW program structure: The multi power meter can be connected via the *General Purpose Interface Bus* (GPIB) interface or the serial RS-232 interface which are both compatible with the VISA and use the same program code. The program structure is implemented using the design pattern of a state machine, shown in Figure 16.

In the *Initialization* state, the VISA resource (i.e. the serial port) is opened and the string `SN250` is sent to the Multi power meter to set the exposure time. All strings use the *linefeed* character (*0x10*) to indicate the end of a command or a response. Subsequently, the string "`MS GM0 GM1 GM2 GM3 GM4 GM5 GM6 GM7`" is sent to indicate that all 8 channels should be read out during the measurement cycle. The measurement cycle is created by looping through the states *Start Measurement*, *Ask For Values*, *Wait Before Read*, *Read*, and *Publish To Shared Variables* until an error is registered or the stop button on the front panel has been pressed. In the *Stop* state, the communication interface is shut down and the loop is halted.

Similar to the other read-out programs within the REACT software, the multi power meter read-out program is supposed to run continuously in the background, read all 8 available channels and publish the read-out values to shared variables. The values can then be selected in top level applications according to their association with a specific process value, such as the relative power of an excitation step.

[16] Gigahertz Optik, Model Optometer P-9801 multi power meter

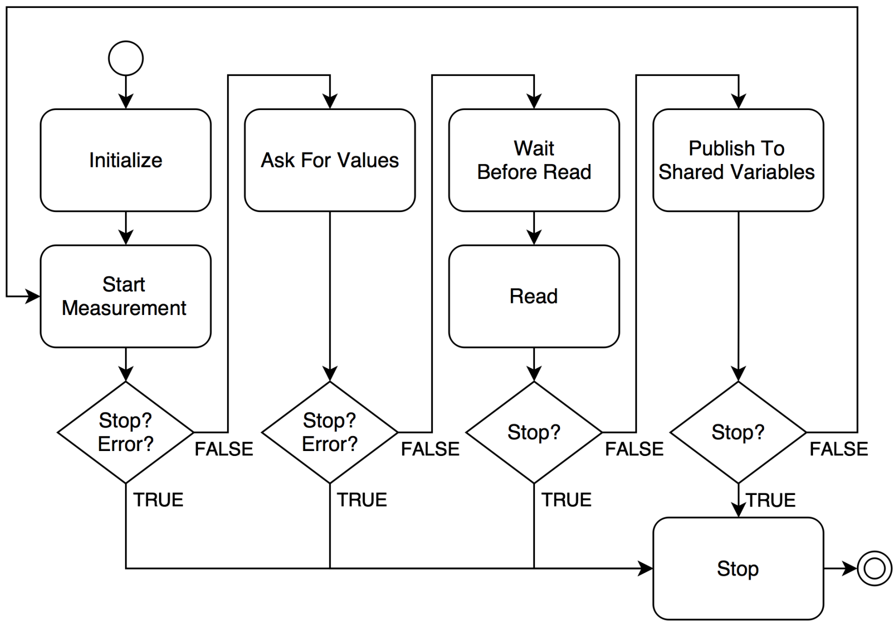

Figure 16: State machine layout of the multi power meter read-out program.

4.2.5 LeCroy WaveRunner 104Xi Scope Readout ■

Flexible parameter measurements: In order to read from analog signal sources such as fast photodiodes[17] or ion detectors, RILIS is equipped with a *digital storage oscilloscope* (DSO) with comprehensive built-in signal processing and measurement functions[18]. The oscilloscope consists of data acquisition electronics built into a standard computer running a Windows operating system and a dedicated application for data processing and measurements. The scope can be set up for stand-alone data acquisition and the resulting measurements can be stored as a configurable 'parameter' value.

A measurement example, the time structure of the laser-ion beam relative to the laser pulse timing trigger, is illustrated in Figure 17: An ion count is recorded in a bin in the histogram corresponding to its arrival time after the trigger signal. This information is accumulated over many laser pulses as a laser-ion arrival time histogram. A time window can be defined as a region of interest and the integral of the histogram within this region is used to determine the ion rate. This has been used to read out the ion beam signal for determining the electron affinity of iodine in an experimental measurement campaign in July 2015 [43].

[17] ThorLabs DET10A
[18] Teledyne LeCroy WaveRunner 104Xi

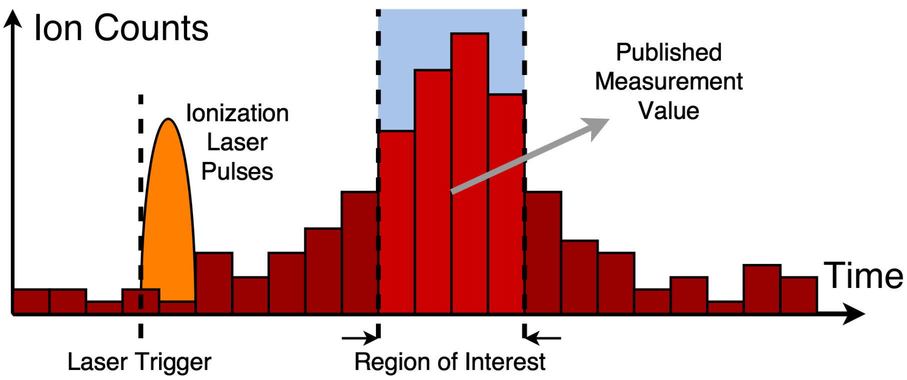

Figure 17: Illustration of the time structure of the laser ion count rate based on a histogram view of consecutive measurements.

The oscilloscope is also used to determine the timing delay in nanoseconds of the narrowband Ti:Sa laser during the scanning process for in-source laser spectroscopy. An analog voltage is read out from a photodiode placed in the laser cavity to register the Ti:Sa laser pulse in relation to the pump laser trigger signal. The centroid position of the photodiode signal is calculated by the oscilloscope software and this value is made available for read-out as a 'laser delay' parameter. Figure 18 illustrates the measurement of the photodiode signal on the vertical axis versus the time on the horizontal axis. After the pump laser pulse arrival (the measurement trigger on the left hand side), the Ti:Sa pulse can be observed as the photodiode response signal. When scanning the narrowband Ti:Sa laser, a horizontal shift in the position of this signal can be observed, as well as a vertical shift, which indicates a change in the output power of the laser. This is crucial information when performing high precision and highly sensitive in-source laser spectroscopy experiments where both the pulse timing and power of the laser have to be actively stabilized. The corresponding top-level stabilization applications are described in 4.5.6 and 4.5.7. The application of these stabilization programs for in-source laser spectroscopy is evaluated in 5.2.3 and 5.2.3.

LabVIEW program structure: The oscilloscope offers similar functionality and interfaces as a standard computer, including a gigabit network connection interface. In using communication SubVIs provided by the manufacturer, the data acquired by the scope can be accessed over the network[19]. The LabVIEW read-out program for the oscil-

[19]The data logging option for the remote connection should be disabled in the oscilloscope scope settings, as this would delay the readout drastically

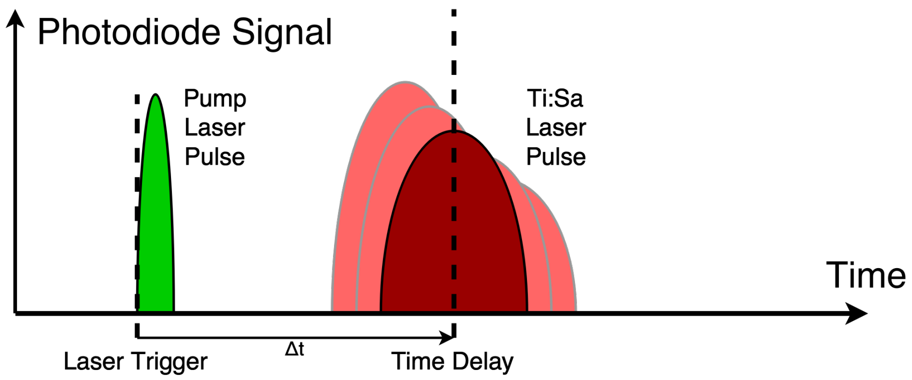

Figure 18: Illustration of the time delay measurement for the Ti:Sa laser pulse.

loscope consists of a single loop, which executes the data acquisition nodes in sequential order. With this setup, the data acquisition and processing can be configured within the oscilloscope while the LabVIEW driver is only responsible for extracting the 'parameter' data and publishing it as a shared variable.

4.2.6 Keithley 6487 PicoAmMeter Readout ★

Direct ion beam current measurements: Similar to the read-out of analog detector voltages by using oscilloscopes, the ion beam current can be measured directly by using amperemeters[20] suitable for the picoampere range. These types of measurements are flexible to set up and are beneficial for the following situations:

- When performing ion source development in the offline mass separator laboratory of ISOLDE, the picoamperemeters provide a direct readout of the ion beam current.
- In 2013, a compact reference ionization chamber was installed in the laser laboratory. The signal read-out from this device will be performed by a picoamperemeter connected to the *secondary electron multiplier*.
- During the negative ion experiment in July 2015, picoampermeter read-outs were used to read the Faraday cup and collimator plates to aid the tuning of the ion beam through the experimental chamber.
- When performing the laser setup for resonant ionization, the Faraday cup of the ISOLDE beamline can be directly connected to the amperemeter to get a faster signal response.

[20] Keithley 6487 PicoAmMeter [44]

LabVIEW program structure: The core functionality of the picoamperemeter read-out program consists of a single loop which continuously acquires measurement values from the instrument. The communication interface is opened before entering the loop and closed after exiting the loop if the user presses the stop button. In case of an error such as a communication time-out, the connection is re-initialized within a 2 second retry period.

However, since the picoamperemeters are frequently used for a wide variety of different applications, the corresponding LabVIEW read-out project has been reworked to incorporate key features of the REACT concept, illustrated in Figure 19, into the application:

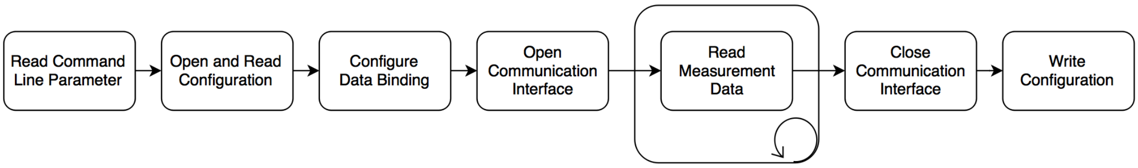

Figure 19: Illustration of a linear program structure suitable for REACT drivers that perform continuous acquisition.

- The top-level read-out program can be run in multiple instances to communicate to multiple instruments.
- A command line parameter is used to specify for each instance the name of a configuration file (e.g. `keithley1.ini`).
- Configuration files contain shared variable deployment path information, hardware connection information, and an information string.
- An information string is provided to associate the read-out value with a meaningful, 'human-readable' name suitable for the current setup.
- The front panel indicator elements displaying the read-out value are connected to the shared variables using data binding, as the data binding path can be defined during the run-time of the program.
- Program settings that have been changed by the user, such as the information string are saved to the configuration file for the driver instance.

In using configuration files and data binding, the driver program becomes more modular and more flexible to configure for different applications. The project structure and implementation concept is intended as an example for developing further drivers within the REACT system that communicate to identical instruments. For this purpose a state machine design pattern should be implemented to improve future maintainability of the program.

4.2.7 ISOLDE Device Readout ♣

Access to ISOLDE beam instrumentation data: An essential aspect of the REACT development is the access to ISOLDE instrumentation data such as Faraday cup current measurements. Prior to 2011, this data was not directly accessed and processed for RILIS operation. The development of the LabVIEW-based data acquisition prototype for the measurement of the astatine ionization potential enabled programmatic recording of combined RILIS and ISOLDE data [10]. The ISOLDE Faraday cup read-out is the primary input value for laser beam optimization, scheme development, and in-source laser spectroscopy tasks. Figure 20 shows the front panel of the Faraday cup read-out program, displaying the ion beam current on the vertical axis versus time on the horizontal axis.

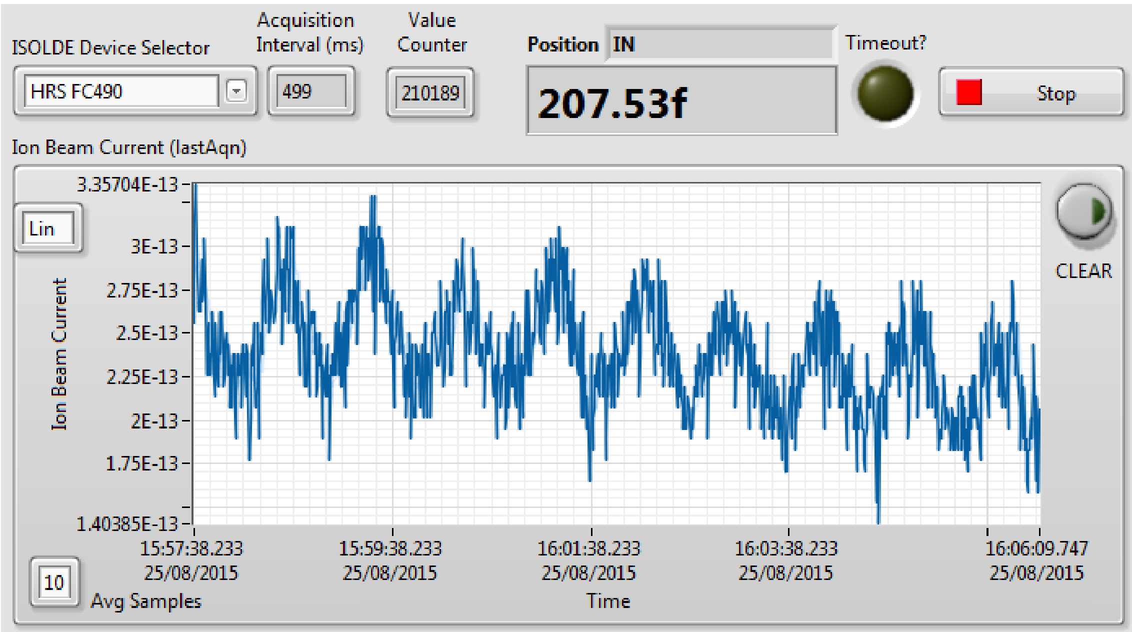

Figure 20: Screenshot of the Faraday cup read-out program front panel.

Since the read-out program accesses the CERN middleware infrastructure, similarly other devices such as thermocouples can also be addressed and their process values can be acquired. For this purpose, devices are registered in a database which can be searched using the *Controls Configuration Data Browser* (CCDB)[21] [45]. The field names, data types, and device relations can be retrieved by searching for the name of the device. This information can then be used to address the desired device and implement the data extraction subroutine.

LabVIEW program structure: Accessing the CERN middleware infrastructure requires the *Rapid Application Development Environment* (RADE) library to be installed on the development computer. This framework is developed by the CERN EN-ICE-MTA[22] section and provides a collection of SubVIs specifically tailored to developing LabVIEW programs that access the CERN controls infrastructure. Figure 21 shows a screenshot of the *RADE Input/Output* RIO palette functions. These provide access to live data from the front-end computers [46].

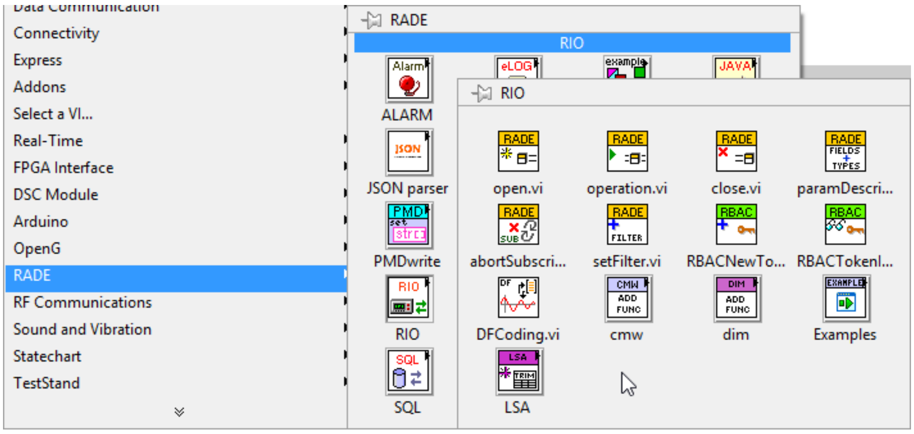

Figure 21: Screenshot of the RADE RIO subVI palette.

The basic program structure is illustrated in Figure 22 and consists of three steps:

Step 1: Open a subscription to the device: This initiates a connection to the device and passes the connection reference to the next programming node.

Step 2 (loop): Get data from the device: In using a subscription to the device, new data is received only when available instead of polling the device in regular intervals.

Step 3: Close the subscription to the device: Once the read-out loop is stopped by the user or due to an error, the connection reference to the device is released and the

[21] The CCDB is part of the *Controls Configuration Service* maintained by the CERN Controls (CO) group within the Beams (BE) Department.

[22] Engineering Department - Industrial Controls & Engineering - Measurement Test Analysis [27]

program is stopped.

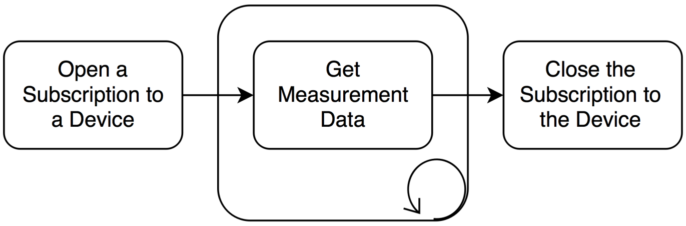

Figure 22: Program structure implementing a subscription loop suitable for reading from ISOLDE devices using the RADE framework.

Future acquisition programs based on this project template could include the read-out of the target heating and the magnet current to enable both logging and warning capabilities through default shared variable functions. The read-out of the separator magnet mass setting could be integrated into the RILIS status viewer program 4.5.3 in order to view and verify the laser setting for the chosen isotope mass.

4.2.8 PSB Telegram Readout ♣

Multiplexed pulsed proton beam: Protons are sent in pulsed bunches from the *Proton Synchrotron Booster* (PSB) to the CERN accelerator complex at an interval of 1.2 s over the course of one supercycle. A supercycle varies in length from about 30 seconds to 60 seconds, depending on the number of experiments that have requested to receive the multiplexed proton beam.

The PSB facility publishes a data structure ('Telegram') each time a pulse is sent, indicating, amongst other data, the proton destination information and the proton bunch number within the supercycle. This data structure is read out by the *PSB Telegram Readout* program, visualizing the supercycle as shown in the front panel screenshot in Figure 23. The upper section shows the previous supercycle structure while the lower section is filled with current proton pulse information from left to right. The display is designed to highlight pulses destined for either the *General Purpose Separator* (GPS) target or the *High Resolution Separator* (HRS) target at ISOLDE. The information about the proton pulse destination serves as a software trigger signal for the RILIS data acquisition software and is used for coordinating laser scans. This trigger signal is propagated when working with connected experiments such as ISOLTRAP to synchronize communication between both setups. The pulsed structure of the proton beams is prominently visible when working with quickly released isotopes and can be complemented with additional proton count and proton current information described in the next subsection.

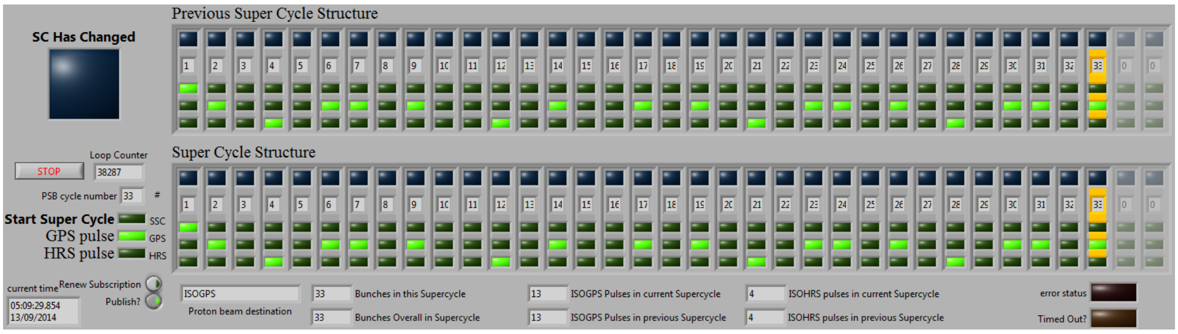

Figure 23: Screenshot of the *Proton Synchrotron Booster* (PSB) telegram read out program which provides timing information about the proton pulses to synchronize the laser scan process.

LabVIEW program structure: Similar to most low-level programs described previously, the PSB telegram readout consists of a single loop implementing the minimal 'open-read-close' data acquisition pattern. In order to access the PSB telegram data structure, the programming nodes of the *Java API for Parameter Control* (JAPC) are used, which are provided with the RADE framework. Figure 24 illustrates the principle structure of the LabVIEW program. In the full program, the data contained on the 'wire' ending in the `Data Out` indicator is evaluated to display and process the proton beam information.

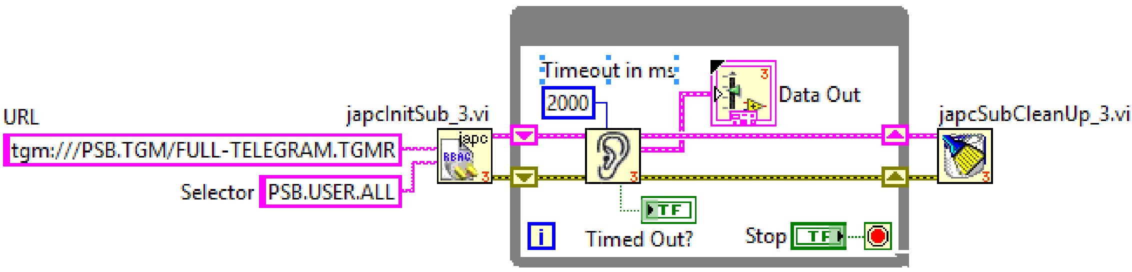

Figure 24: Illustration of the program structure for reading the *Proton Synchrotron Booster* (PSB) telegram data structure.

4.2.9 PSB PPP and PC Readout ♣

Correlated with the proton beam distribution telegram described previously, information about the number of protons in each pulse (*Protons per pulse*, PPP) as well as the resulting integrated *proton current* (PC) is provided in regular intervals. The production rate of the ions of interest is directly proportional to the intensity of the proton beam impacting on the target. This is especially true for short-lived and exotic radioactive ion beams. Recording this information is important for scaling measurement data during post-analysis of different scans obtained different proton intensities. The proton beam intensity information gathered in parallel to the ion beam signal during an in-source spectroscopy laser scan is also helpful for identifying possible short-time fluctuations in the proton beam. Figure 25 shows the proton current data obtained during a laser scan (from left to right) where the proton current value was raised from $\approx 1.7\,\mu A$ to $\approx 2.0\,\mu A$ at about one third into the scan range and the proton beam was lost near the end of the scan.

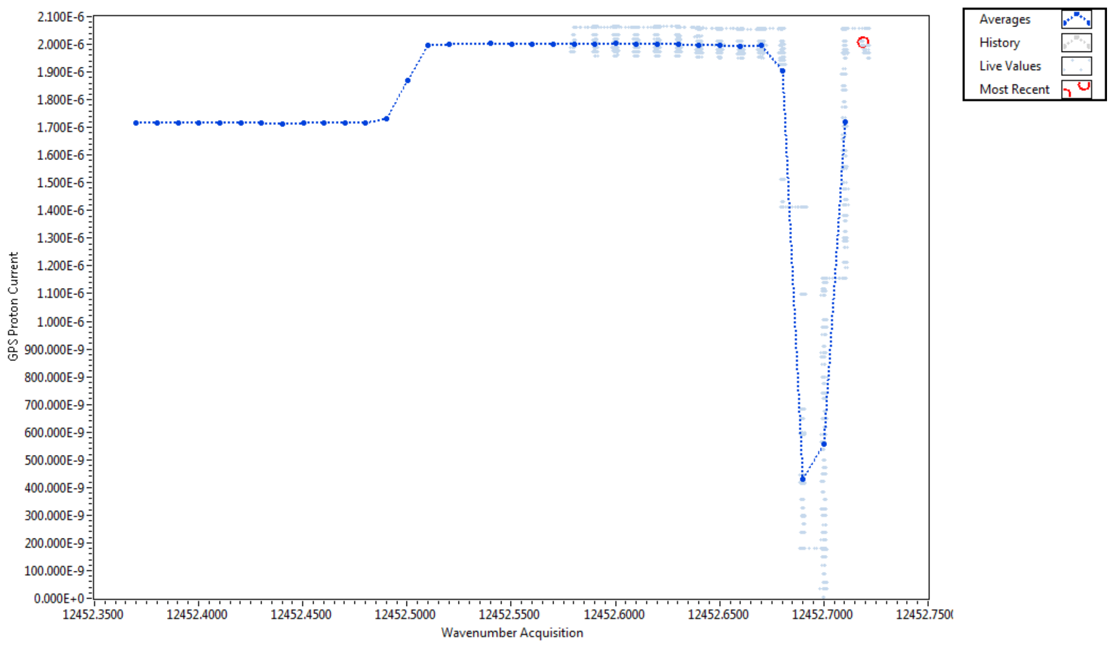

Figure 25: Plot of the *Proton Synchrotron Booster* (PSB) proton current information obtained during a laser scan. The plot indicates a raise and a loss in proton current.

4.2.10 DAQ Card in PXI ♣ ■

Analog and digital inputs and outputs: Some applications within the RILIS laser laboratory require the ability to measure and generate analog or digital signals. These applications range from acquiring analog detector signals to sending and receiving digital TTL[23]-level signals to collaborating experiments in order to synchronize the measurement process. For this purpose, the RILIS PXI[24 25] system is equipped with a *data acquisition* (DAQ) card[26] which facilitates the simultaneous measurement and control of multiple digital and analog values.

TTL communication with experiment setups: A single-loop program is used to generate and receive output and input TTL signals to synchronize a scan of the RILIS lasers with the alpha-decay 'windmill' detector setup. This program makes use of *DAQ Assistant* Express VIs, pictured in Figure 26, to access the digital inputs of the data acquisition card and provide them as a Boolean array. The *DAQ Assistant* Express VIs are pre-programmed and dynamically configurable SubVIs to access NI hardware with minimal programming effort.

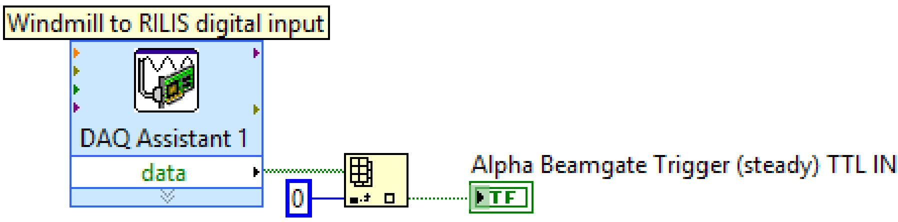

Figure 26: Screenshot of the DAQ Assistant Express VI node allowing for simple configuration and access of National Instruments Hardware.

Analog read-out of position sensitive detectors (PSDs): Another application [48] is performing analog measurements of the 0 V to 10 V output signals of *position sensitive detectors* (PSDs), which are placed within the laser beam reference area as part of an autonomous system to stabilize the laser beam positions. The detectors are set up by default and reading their signals provides a relative measurement of the laser power of the position-stabilized laser beam.

[23]Transistor-Transistor Logic (typically 0 V 'LOW' to 5 V 'HIGH')
[24]PCI eXtensions for Instrumentation
[25]Peripheral Component Interconnect
[26]Model: NI PXIe-6363, X Series DAQ (32 AI, 48 DO, 4 AO) [47]

4.2.11 RMPS Communicator ★

RILIS machine protection system: As a step towards autonomous machine protection and operator support for on-call operation, an environmental monitoring system, the *RILIS machine protection system* (RMPS), for the dye lasers was installed in 2013 to measure ethanol content in the air, dye flow rate, and dye temperatures. The system was specified by RILIS operators and developed in conjunction with the CERN EN-STI-ECE[27] section to run independently from all other RILIS equipment. The corresponding specification document can be found in [49]. Figure 27 shows the specification overview for the RMPS, indicating the required sensor read-outs and input signals on the left.

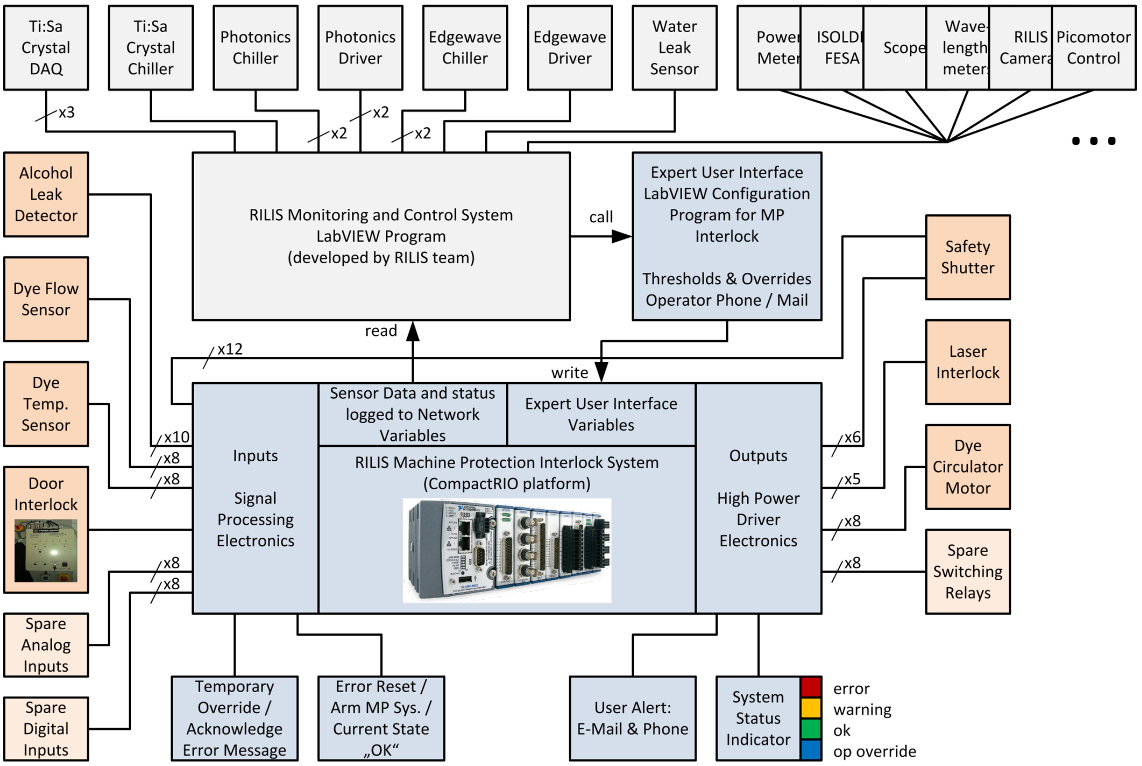

Figure 27: Overview diagram of the RILIS Machine Protection System concept. [49]

The central part represents the main controller unit based on a *National Instruments CompactRIO* platform [50] with command inputs and status indicators depicted below. Outputs and actuators of the system are shown on the right consisting of safety shutters, laser interlock signals, and relays to switch the dye circulator motors. The top part of the diagram shows the connections of the *RILIS Monitoring and Control System* (i.e.

[27]Engineering Department - Sources, Targets and Interactions Group - Equipment Controls and Electronics Section

the REACT software system) which reads sensor values from the RMPS controller and communicates with its *Expert User Interface* LabVIEW program.

The expert user interface LabVIEW program developed by the CERN EN-STI-ECE section is used to set alarm and warning threshold levels for the sensor readouts and to switch relays to power the dye circulators. If the sensor thresholds are exceeded, the program sends warning messages to a dedicated RILIS operator mobile phone and to the RILIS operator e-mail address, allowing for an early intervention. In the case of a severe error, such as a hazardous dye leak, the machine protection system is capable of closing laser safety shutters and cutting the power to the dye circulators.

Long-term sensor read-out: The RMPS runs independently from other hardware in RILIS and is continuously reading sensor data in approximately 500 ms intervals. This sensor data is published within a shared variable data structure that is hosted on the *CompactRIO* controller and can thus be accessed via the CERN technical network. A *RMPS Communicator* LabVIEW project has been developed to read out and visualize the acquired sensor data and communicate with the expert user interface of the machine protection system. Figure 28 shows the front panel of the sensor data visualization, indicating a tabbed graph display with the *Alcohol Leak Sensors* readout currently visible. There are currently 12 alcohol leak detectors present in the system which are placed near the oscillator and amplifier cuvettes representing critical points within the dye lasers. The image shows the uncalibrated sensor read-out amplitude on the vertical axis versus time on the horizontal axis. The image was taken after a dye change had taken place and an exhaust vent was activated to reduce the ethanol concentration in the air. The peak on the right was caused by switching off the exhaust to check the dye solvent dissipation rate from the dye circulators to estimate the need for further interventions to ensure closed and safe system operation.

4.3 Control Driver Programs

The control driver programs address the requirement of interacting with RILIS equipment to set configuration values or to manipulate motorized optomechanical elements both locally and remotely. The programs within this category are launched on demand and are intended to complement the original software supplied by the hardware manufacturer where applicable. The software supplied with the equipment provides comprehensive control and configuration options when working locally in the laser laboratory. Remote

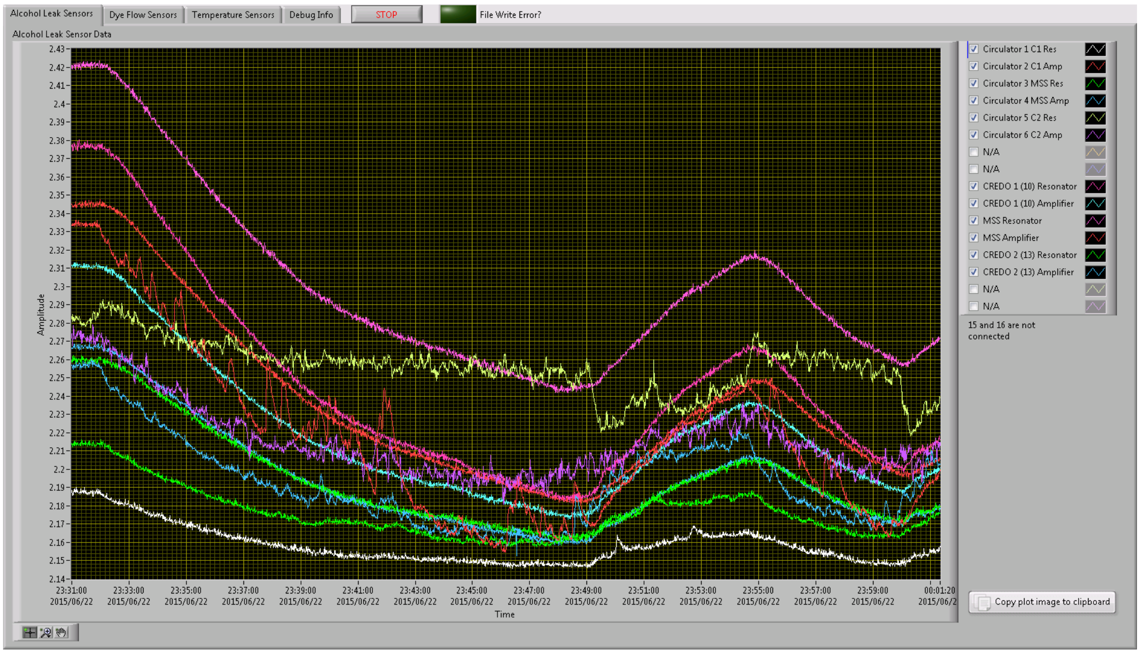

Figure 28: Screenshot of the alcohol leak detector visualization program.

control requires the implementation of driver programs in order to facilitate the connection of the equipment to the CERN network. In conjunction with the monitoring driver programs and top level applications, modular closed-loop feedback stabilization algorithms were implemented to subsequently automate stabilization of the laser parameters.

4.3.1 Picomotor Driver (Position Control) ♣

Laser beam position control: Up to four laser beams can be sent to the GPS target or the HRS target through the vacuum windows of the corresponding mass separators. In order to manipulate and optimize the laser beam positions within the ion source, there are eight motorized *launch mirror mounts* installed on the optical table, four for each target location. The optomechanical mounts are motorized by 2 or 3 *Picomotor Piezo Linear Actuators* offering a 30 nm positioning resolution [51] for the horizontal, vertical, and combined axes of the launch mirrors. In order to control the actuators, two stacks of four *Picomotor Driver Modules* (4 channels each) and one *Open-Loop Picomotor Controller*[28] is connected to the RILIS-PXI system via the RS-232 interface. A joystick connected via

[28] New Focus Picomotor Ethernet Controller - Model 8752
New Focus Intelligent Picomotor Driver - Model 8753
New Focus Picomotor Joystick - Model 8754
AC Power Adapter - Model PW-070A-1Y24D0

a cable directly to the controller can be used to select and to manipulate the individual axes of the mirror mounts. An example image of the picomotor control components is shown in Figure 29.

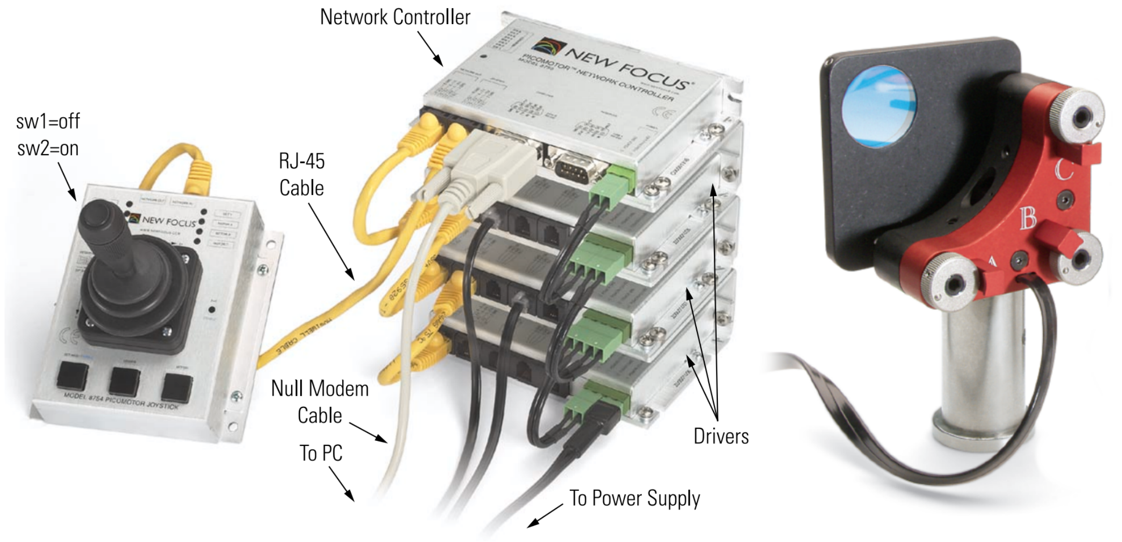

Figure 29: Picomotor system example image. The controller and driver stack is pictured on the left, a motorized mirror mount is pictured on the right.

Wireless gamepad control: A LabVIEW driver application has been developed in order to provide a more comfortable local control as well as remote control of the picomotors. When using the joystick directly connected to the controller, the RILIS operator has to select the correct driver module and channel individually in order to move the correct axis. This selection process proved to be tedious and not intuitive and often resulted user error and movement of the wrong axis. To improve this, the LabVIEW program features position control using a wireless gamepad[29], pictured in Figure 30, as a more comfortable input method. The color-coded beam paths mentioned in 4.2.1 correspond to the colored buttons on the right side of the gamepad which are used to select the corresponding mirror to be moved. The mirror can then be moved in stepping intervals by using the four-way switch on the left side of the gamepad. The movement step size can be increased or decreased by the factor of 2 by pressing the frontal right and left trigger buttons on the gamepad.

[29] Logitech F710 Wireless Gamepad

Figure 30: Wireless gamepad to control the picomotor *Piezo Linear Actuators* of the RILIS *launch mirror* optomechanics.

LabVIEW program structure: The wireless gamepad is recognized by LabVIEW as a multi-axis and multi-button joystick and can therefore be addressed by pre-defined corresponding programming nodes. The LabVIEW control program consists of two independently running loops illustrated in Figure 31: The top loop contains an event structure to handle interactions with the GUI and to process custom user events sent by the bottom loop. The bottom loop polls the joystick (gamepad) in regular intervals of 50 ms and sends custom user events, once a value change is registered.

When the user presses a button on the gamepad, the changing value is registered in a Boolean array, which represents the buttons. This triggers a user event notification to be sent to the event handling loop in order to be translated in motor movement by communicating with the motor controller. The communication with the motor is performed by sending and receiving command and response strings to the motor controller via the serial RS-232 interface. The command strings are programmed into SubVIs[30] to be called from multiple locations throughout the program. Figure 32 shows the block diagram code that performs a relative movement of the picomotors: From the left, input parameters for error codes, the communication interface, the step size, the channel selection and the driver number are received. The following command sequence (shown from left to right) is necessary to perform a relative movement of the picomotors:

[30] c.f. functions or methods in textual programming languages

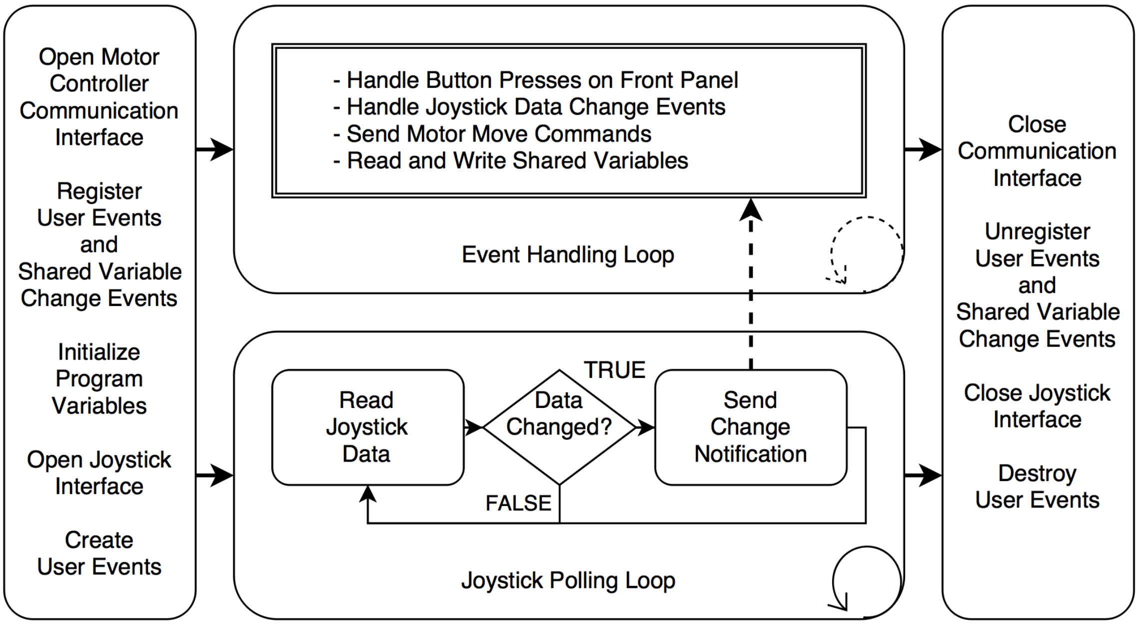

Figure 31: Structure of the picomotor control program: The top loop handles events received from the GUI and from the bottom joystick polling loop.

1. Disable the attached joystick (only one active input device is allowed at a time).
2. Select the desired driver and channel number.
3. Set the movement speed of the motor (in Hz).
4. Execute a relative movement using the previously configured values.
5. Get the status from the motor to determine successful completion of the movement.
6. Enable the attached joystick.

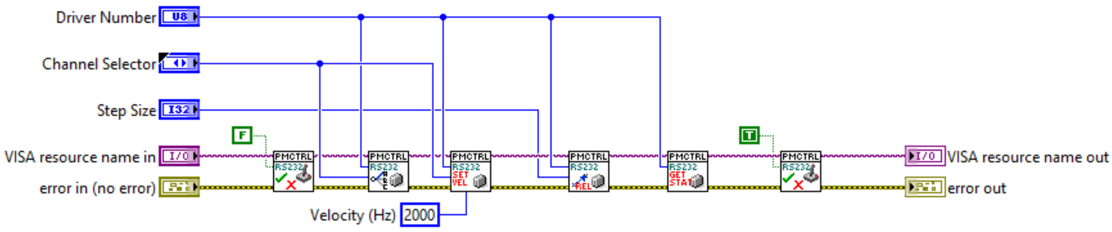

Figure 32: Block diagram code to perform relative movement of the picomotors. Each SubVI encapsulates a serial command and response sequence.

The picomotor control program communicates with the beam position monitoring program (see subsection 4.2.1) via shared variables to highlight the color-coded camera frame of the currently selected laser beam path as a visual aid and to reduce the risk of accidental movement of the wrong mirror. The current version of the program is mainly used during the setup phase of RILIS and during interventions performed from within the laser laboratory itself. However, remote control of the laser beam position control could be implemented in future program versions by exposing the position controls likewise as shared variables.

4.3.2 Arduino XY Stepper Driver ♣ ★

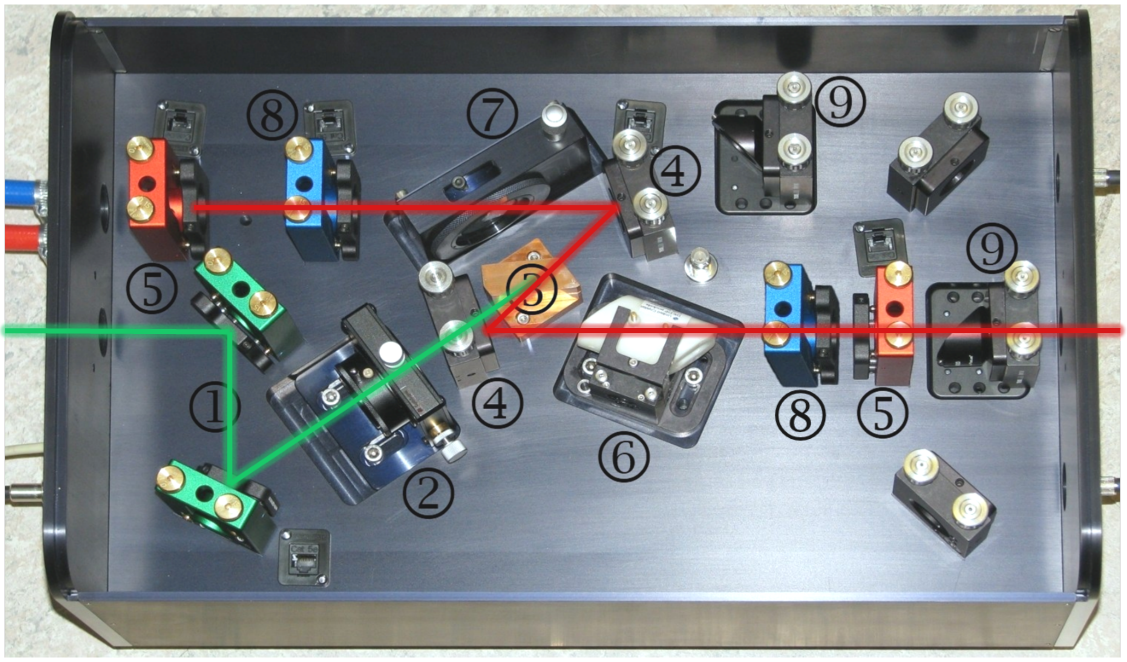

Figure 33: Optical layout of the Ti:Sa laser used in the RILIS for narrow band operation.

Hardware setup of motorized optomechanical elements in Ti:Sa laser: The Ti:Sa lasers, added to the RILIS setup in 2011 [14], feature design optimizations for ease of modifying optical elements required for wavelength selection and tuning. The complete optical layout is shown in Figure 33 and consists of the following elements:

(1) Pump laser beam mirrors

(2) Pump laser beam focussing lens

(3) Titanium:Sapphire crystal

(4) Concave Ti:Sa laser beam cavity mirrors

(5) Output coupler mirror (typical 96 % reflective)

(6) Pockels cell for quality-switching of the laser cavity

(7) Lyot filter

(8) Up to two etalons

(9) Reference pickup for wavemeter measurements or alignment laser

(10) Photodiode for pulse timing measurements

The XY optomechanical mounts for the etalons (8) have been fitted with stepper motor-driven linear actuators to enable remote manipulation of the wavelength of the laser. The stepper motors are driven by a custom-built Arduino-based [52] electronics described in more detail in [16].

LabVIEW programs: The LabVIEW program to control the Arduino stepper driver consists of a single loop that handles the communication between the shared variables and the microcontroller hardware. The serial RS-232 interface is used to send and receive strings of minimal length of the pattern `<x-position>X<y-position` to be parsed by the Arduino software. The minimalistic communication protocol at a rate of 38400 Baud[31] and a minimum loop iteration time of 5 ms was implemented to ensure a quick response time of the microcontroller to set new motor positions. This way, scanning and stabilization functions could be implemented with a loop iteration time between 10 ms and 100 ms, matching the typical acquisition rate of the wavemeter.

The driver software for etalon movement has been updated to use data binding between front panel control and indicator elements to shared variables hosted on the local computer where the software is started. This allows for the programmatic change of the data binding path at run-time of the VI when configuring multiple driver programs to run in parallel. This was necessary to enable parallel operation of a Ti:Sa laser in narrow-band configuration while stabilizing an additional Ti:Sa laser.

[31] Baud: Symbols per second i.e. waveform changes per second. In RS-232 communication, the bit rate corresponds to the baud rate.

4.3.3 Credo Laser Control ★

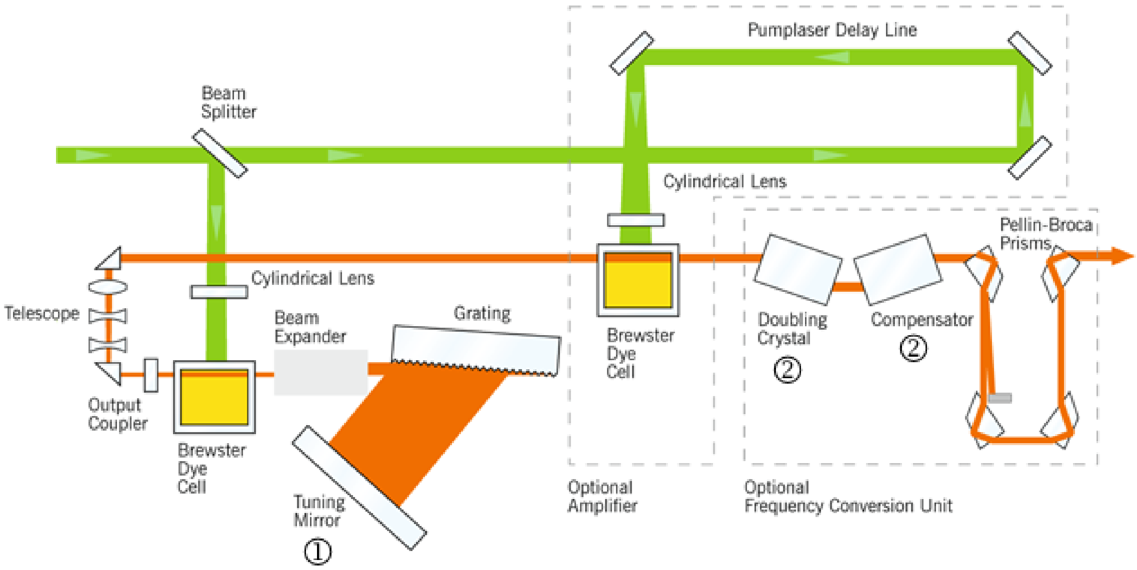

Figure 34: Optical layout of the Sirah Credo dye lasers. [53]

Local and remote software control options: The wavelength of the dye lasers[32] can be controlled locally within the laser laboratory using the software supplied by the manufacturer. Besides direct control of the *Tuning Mirror* ① and the *Doubling Crystal* assembly ②, both shown in Figure 34, this software offers a calibration table to tune to a specific wavelength, as well as a configurable scan function. However, this software is required to run on the computer that the laser is connected to, which does not allow remote control. In addition, the software has to be installed for each laser separately in order to make use of independent configuration files containing device-specific hardware information. In order to integrate the dye lasers into the REACT architecture, a device driver has been developed which exposes the motorized controls of the *Tuning Mirror* position and the angle of the *Doubling Crystal* in the *Frequency Conversion Unit* (FCU) of the laser as shared variables. This driver program makes use of the configuration files of the original software to determine the hardware connection interface of the controlled laser. Both the original software and the REACT driver cannot be run simultaneously because the RS-232 hardware connection cannot be shared. Thus, the original software

[32] Sirah Credo [53]

is used locally when setting up the lasers or performing automated scans. Subsequently, after exiting the software program the REACT driver is started, enabling remote operation and long term laser wavelength stabilization through the use of a corresponding top-level VI.

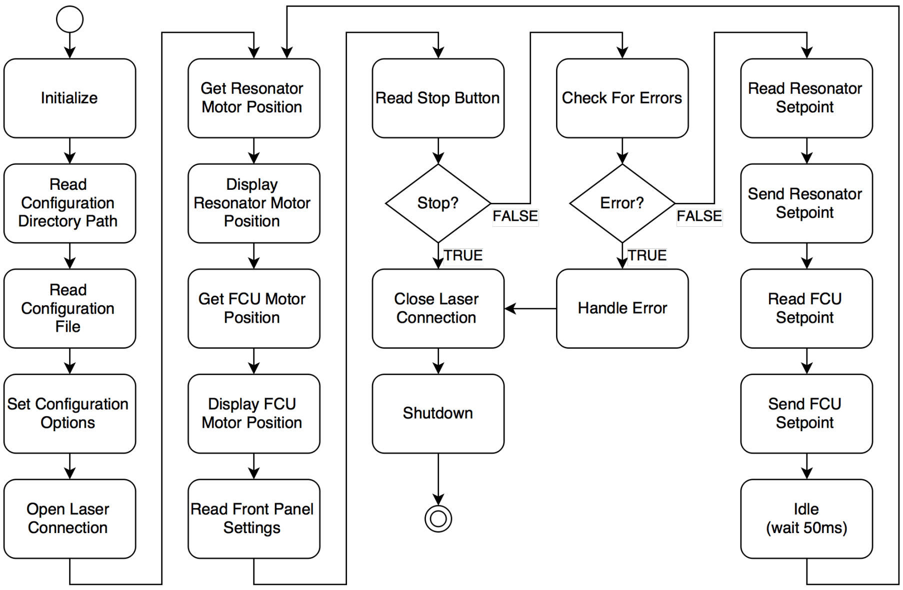

Figure 35: State machine diagram of the CREDO laser driver program.

LabVIEW program structure: Figure 35 shows the state machine diagram of the Credo laser driver developed for the REACT framework: During the initialization phase, the path to the configuration file of the laser to be controlled is read from a command line parameter supplied to the program. Individual control program instances for each laser can be started this way by external scripts or a batch file supplied to the user. A connection to the laser is opened and the current motor position values of the *Tuning Mirror* position and the angle of the *Doubling Crystal* are read and published as shared variables. Subsequent program steps include reading the front panel settings, checking if the front panel stop button was pressed and checking for errors. If no error occurred, new motor position setpoints are read from the shared variables and sent to the laser. An idle time of 50 ms completes the loop and releases control of the CPU for other programs to run.

With this driver program running, it is possible to control the laser wavelength and harmonic generation assembly remotely by manually setting the corresponding motor setpoint shared variables. A small top-level program that can be run on any technical network computer has been developed to allow for manual control of the shared variable setpoints. Using these shared variables in combination with the wavemeter read-out variables enables the implementation of stabilization and scanning routines as modular top-level applications. These have been used routinely in 2015 for 'on-call' operation and were also suitable, with modified parameters, for wavelength stabilization of the Ti:Sa lasers.

4.3.4 Motorized Waveplate ★

Background: To enable laser power attenuation, the polarized laser light can be sent though a rotating waveplate and a polarizing beam splitter cube. By changing the axial rotation of the waveplate, the polarization plane of the laser light is rotated, resulting in a relational splitting in horizontal and vertical proportions. An illustration of the working principle is given in Figure 36 taken from available commercial assemblies applying this technique [54].

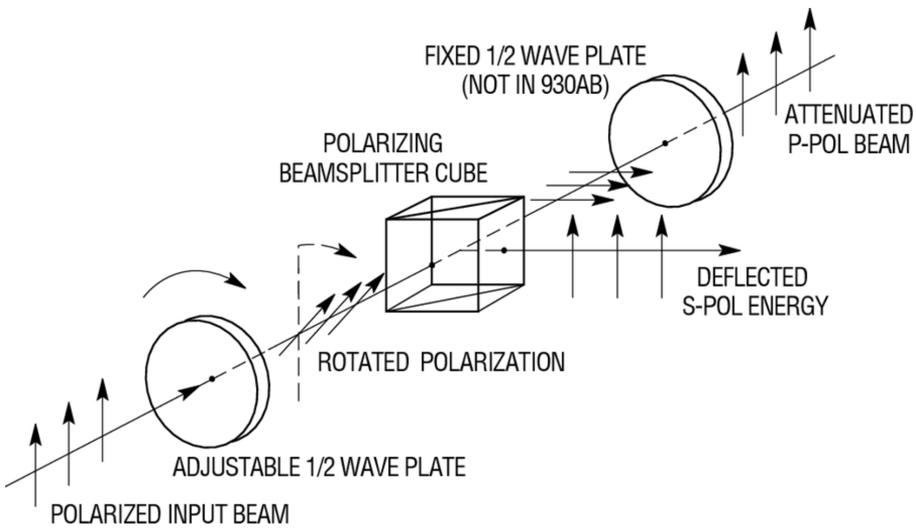

Figure 36: Illustration of laser power attenuation using rotating waveplates and polarizing beam splitter cubes. [54]

Implementation: For RILIS operation, a comparable approach has been taken in conjunction with the harmonics generation unit: Efficient generation of higher harmonics laser light requires matching the orientation of the polarization of the laser beam with the orientation of the polarization axis of the harmonics generation crystal. By rotating the polarization of the laser beam before entering the harmonics generation unit, the resulting output power of the doubled laser beam can be influenced. For this purpose, the rotating waveplate is fixed in a stepper motor-actuated optomechanical mount, shown in 37.

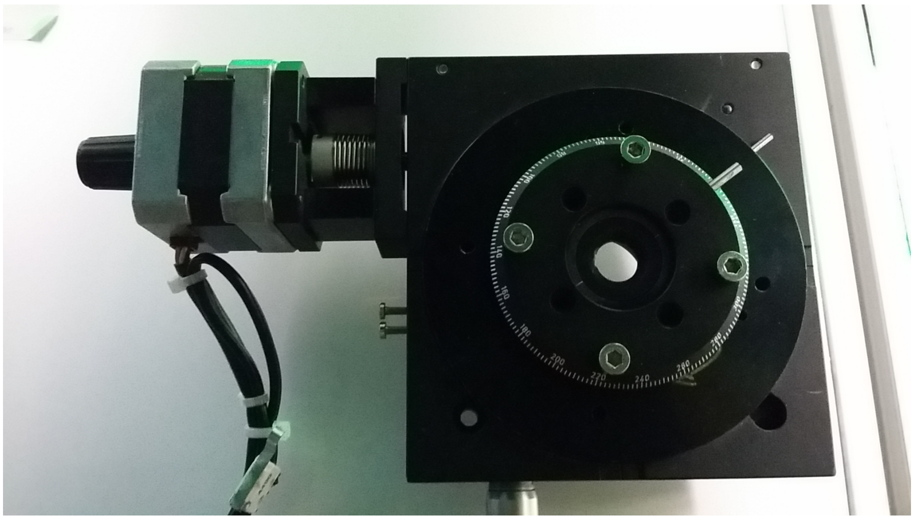

Figure 37: Photo of the waveplate mounted in the stepper motor actuated optomechanical mount.

In order to control the stepper motor attached to the optomechanical waveplate mount, a copy of the Arduino-based stepper motor driver used for tilting the etalon mounts within the Ti:Sa laser has been built. The same LabVIEW control program as described previously in 4.3.2 can be used to communicate with the hardware driver and allows for manual control of the stepper motor position. The stabilization routine is implemented as a top-level application described in 4.5.7.

4.3.5 Quantum Composers Delay Generator Driver ■ ★

Timing control: Timing control of RILIS lasers is provided by an 8-channel digital delay generator[33]. Each pump laser is connected to its own channel (designated A through H) and is triggered with a specific delay to a master clock signal designated T_0.

Channel H represents the master clock reference signal which is distributed via a separate 12-channel distribution box[34] throughout RILIS and the ISOLDE physics network patch panels. The T_0 signal is used as the trigger reference for scopes and to synchronize with user experiment setups. The pump lasers are connected to channels A through D,

[33] Quantum Composers 9000 Series

[34] Optocoupler-isolated 12x TTL fanout (Meinberg SDU-OC-TTL)

triggering the dye pump laser (*Edgewave*), the non-resonant ionization step laser (*Blaze*), and the two Ti:Sa pump lasers (*Photonics* 2 & 3). Channels E through G are used to trigger the Pockels-cell q-Switches of the individual Ti:Sa lasers if necessary.

The adjustment of the timing delay between the lasers is usually only necessary during the setup for a specific ionization scheme. In this case it is sufficient to use the manual control buttons locally on the delay generator to input the necessary changes. However, scanning the wavelength of the Ti:Sa laser causes a timing shift of the laser pulse with respect to the pump pulse. Without compensation for this shift, the measurement signals recorded during e.g. an in-source spectroscopy run will be distorted. In extreme cases a complete signal loss of ion signal can occur due to the loss of temporal overlap of the laser pulses involved in the multi-step ionization scheme.

REACT implementation work: The delay generator can be remote controlled via the RS-232 interface to set new delay values programmatically. A corresponding proof-of-concept remote control program has been revised and adapted for use in the in-source spectroscopy runs in April and May 2015. The program was modified to minimize errors due to invalid delay values being entered. Figure 38 shows the block diagram structure of the delay generator program with two nested loops.

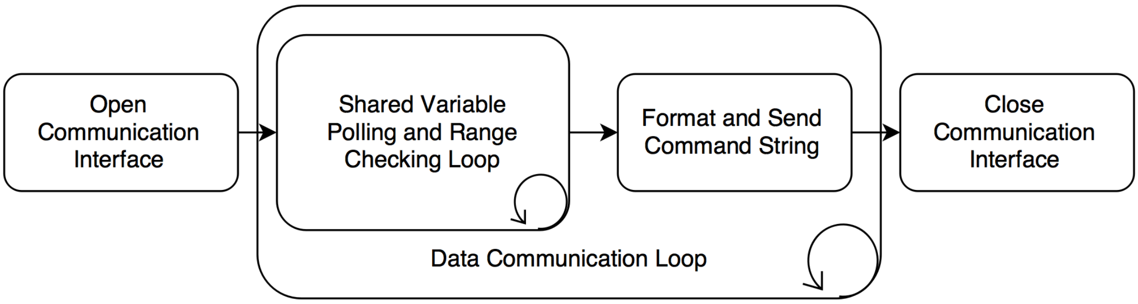

Figure 38: Block diagram structure of the of the delay generator control program.

The inner loop is polling a shared variable, containing the desired delay setting, in 100 ms intervals for changed values. It also performs range checks for entered values and reads the front panel buttons. Once a valid delay change request within the range of ± 250 ns is registered, the inner loop is stopped and the numerical delay value is converted to a command string which is sent to the delay generator, iterating the outer loop.

The current version of the program addresses one specific channel of the delay generator since it was implemented specifically to act as the driver program for the Ti:Sa timing stabilization. Future versions of this program could be extended to control all channels.

For example, this could facilitate an automated timing scan during the laser setup phase to ensure optimal temporal overlap of all of the pulses of the lasers used in the ionization scheme. For this purpose, the state machine design pattern should be applied to the program to modularize the necessary safety checks as reusable program states.

4.4 Infrastructure, Data Distribution and Storage

The data communication aspect of the REACT framework implementation is its unified structure of data distribution through LabVIEW shared variables. This is represented by the middle layer of the REACT concept diagram, highlighted in Figure 39 below.

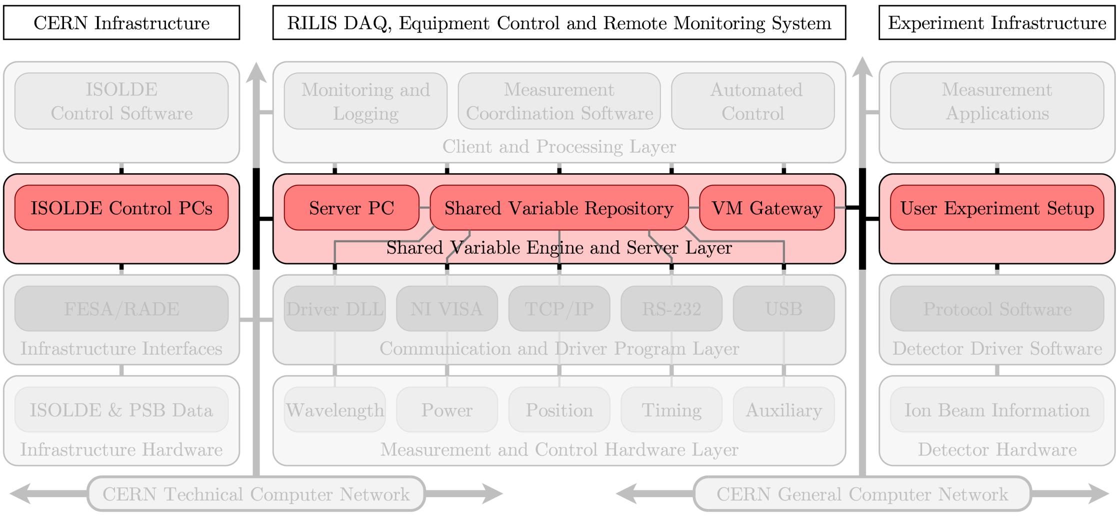

Figure 39: Middleware and data communication layer of the REACT framework.

4.4.1 Shared Variable Engine Processes

As outlined in the conceptual design in chapter 3, the REACT framework is based on the usage of LabVIEW shared variables as a data repository and as a data distribution tool.

Network shared variables were introduced in LabVIEW version 8 and are easily integrated in to any *Virtual Instrument* (VI). In conjunction with the *Datalogging and Supervisory Control* (DSC) module, the shared variable engine provides additional high level programmatic access to alarming and logging functions. Furthermore, a security option can be activated through an integrated security mechanism.

The central aspect of program development according to the REACT concept is to use shared variables as a communication interface between self-contained program modules.

Specific driver programs communicate directly with the hardware and can be expanded and developed according to hardware changes or feature requests. The acquired values from the driver programs are published in device specific shared variable engine processes. Programs in the user interface layer can access these defined interface variables.

Figure 40 shows two use case examples for the communication process through shared variables: The left diagram (a) represents a decoupled controller and driver structure where the user interface program can be easily adapted while keeping the driver unchanged. The right picture (b) represents a specialized measurement application that can subscribe to shared variables to record the values of interest. Corresponding examples are the credo laser wavelength stabilization (a) and the RILIS data recorder application (b).

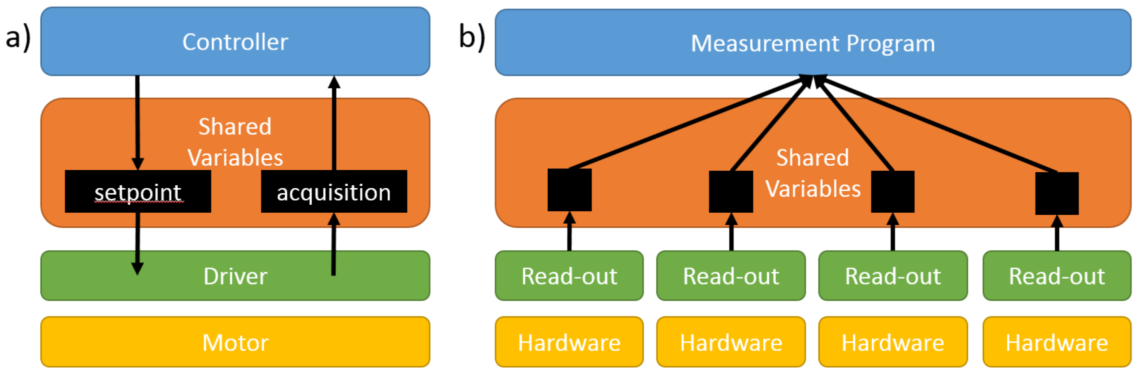

Figure 40: Schematic illustration of the shared variable usage within the REACT framework.

4.4.2 Virtual Machine Gateway

The CERN network is separated into a *General Purpose Network* (GPN) and a *Technical Network* (TN). The general purpose network connects office computers and non-critical IT-systems and provides Internet access. The technical network is specifically reserved for interconnecting machine control computers and as such is protected from unauthorized external access.

A *Virtual Machine* (VM) instance acting as a gateway between the GPN and the TN has been configured in order to expose selected acquisition values present in the technical network. Shared variable communication is achieved by running specific shared variable engine processes that mirror selected process values to the general purpose network, making them available to ISOLDE users. This is achieved trough the mechanism of creating an alias to the TN process that hosts the variable of interest.

The concept has been successfully applied to establish connections to user experiments for both monitoring and control purposes, e.g. in operating the narrowband Ti:Sa control software from the CRIS experiment setup. Furthermore, due the compatibility of shared variables with established industry standards such as *Open Platform Communications* (OPC), the values can also be accessed through corresponding library functions in other programming languages such as Python. This has been demonstrated by using the software packages *Python 2.7 (32 Bit)*, *Python for Windows extensions (32 Bit)*, and *OpenOPC for Python*.

4.4.3 Data Recording and Logging Methods

The data recording of measurement values acquired by RILIS hardware is necessary for experiments and development work while the logging of long-term trends and program behaviour represents an important aspect for reliable operation and diagnostics. For this purpose, two main use cases can be distinguished: specific (x y) data recording for experimental purposes and general long-term (y t) data logging to provide trend information.

Recording of experimental data has to be flexible and must be able to be changed on demand. This was achieved by implementing a dedicated program for in-source laser spectroscopy recording [36] and its application for an experiment is described in 5.2.2. Additionally, simple logging programs such as the *Shared Variable Logger* described in 4.5.5 can be easily developed to access selected shared variables for diagnostic purposes.

Long term logging can be configured optionally by making use of the *Citadel* database system and the DSC module available from *National Instruments*. To enable this logging system, a database file system must be configured on a host computer by using a management program included with the DSC module. The integrated logging feature of the shared variables can then be activated by configuring the path to the database either programmatically or by using the *Distributed System Manager* (DSM), which is a standard shared variable management tool shipped with LabVIEW. With this long-term data recording mechanism, the logging interval, the warning and alarm value ranges, as well as a deadband[35] region can be configured without additional programming requirements. Further details are described in [55]. The data can be retrieved and analyzed using the *NI Diadem Environment* [56]. This long-term data recording method complements the concept of using shared variables within the REACT framework and can be enabled in the course of future developments.

[35] Consecutive values in the deadband region are not recorded.

4.5 Top-Level Utilities

The user interface and control program component of the REACT framework implementation is represented by the top layer of the REACT concept diagram, highlighted in Figure 41.

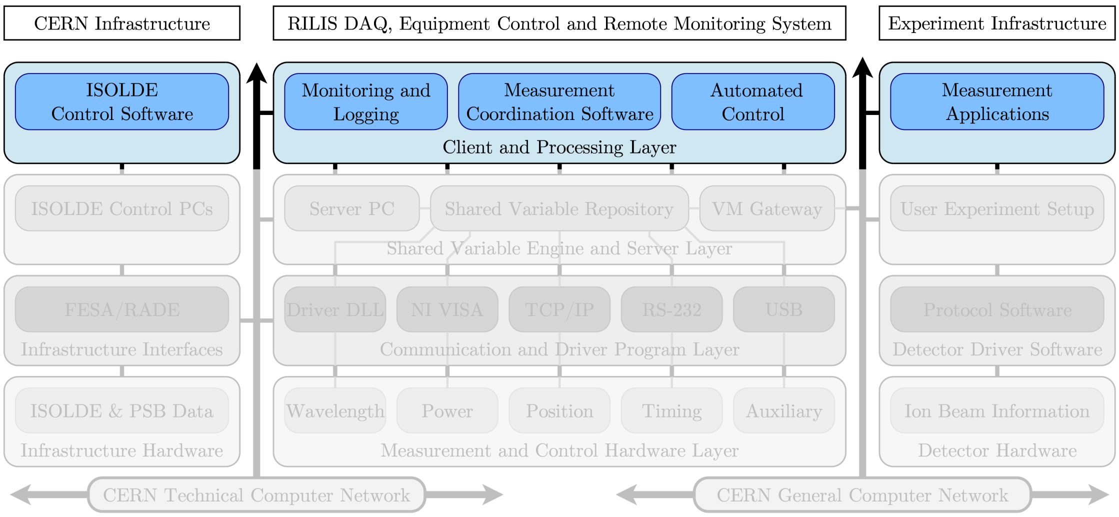

Figure 41: Highlighted user interface layer of the REACT framework.

The programs and composite applications within this layer represent custom tools for the operators to exert control over RILIS equipment. These tools can provide either direct control by manipulating setpoint shared variables or implement stabilization algorithms to simplify or to automate standard tasks. A key feature of the REACT concept is that these top level programs can be written on demand by the operator to enable a certain task, making use of the data provided by the low-level driver programs.

4.5.1 LaserIonSourceMAPper ■

Ionization laser beam position scan: During the setup phase of the RILIS, a manual 'position scan' is performed for each laser beam that is used. This is to determine the optimal position of the laser beams within the source to ensure a high ionization rate. For this purpose, the laser beams are moved in the X and Y directions with the beam position control program described in 4.3.1 while observing the ISOLDE Faraday cup ion beam current read-out on the *ISOLDE Device Readout* program described in 4.2.7 or a Java application running on a Linux computer displaying the ISOLDE controls GUI. The movement of the beam is verified on the *Camera Driver (Position Monitoring)* display described in 4.2.1, which provides an X and Y value of the centroid calculated from the laser beam image. By displaying the ion beam current value dependence on the X and Y position values of the laser beam in an intensity graph, the laser beam positions within the ion source can be 'mapped' to identify a region with the highest ionization value. Figure 42 displays the resulting intensity graphs obtained during the position scan of two different laser beams.

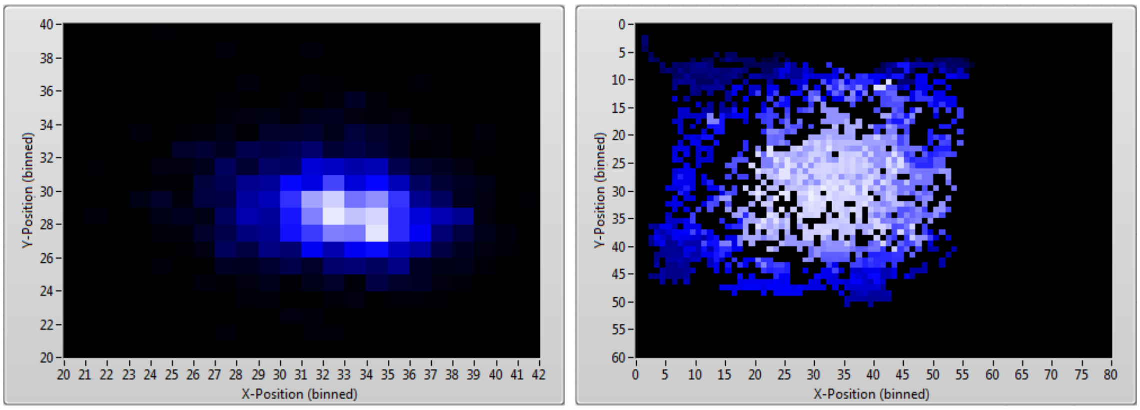

Figure 42: Intensity graphs displaying the ion beam current versus the laser beam position in the laser ion source mapper program. A zoomed view was chosen for the left image while the right image shows the default binning resolution obtained for another laser beam.

LabVIEW program: In a single-loop program, a matrix data structure is created to hold the acquired ion beam current values. The dimension of the matrix is determined by the desired binning factor: The camera image of the laser beam position monitoring software is scaled to 800 by 600 pixels in size. In applying a binning factor of 10, the intensity graph matrix comprises 80 by 60 tiles. The intensity value for each tile is determined by the ion beam value readout obtained for a position within this grid.

The *Laser Ion Source Mapper* application was developed by RILIS operators [57] making use of the available shared variable process values and represents a typical example of extending the REACT software collection with customized tools to support the laser setup and operation procedures.

4.5.2 RILIS eLogbook Posting Tool ♣

Several experiment setups at CERN use an electronic logbook system which is integrated into the machine control infrastructure. At ISOLDE, electronic logbooks are available for

RILIS, for the HRS, and GPS separator beam lines. The latter two are central channels of information exchange for machine operators and users involved in the current working setup and on shift duty. Typical information written into the logbooks are status reports of the current machine conditions and can include numerical settings for beam instrumentation equipment, screenshots of machine control panels or reference Faraday cup measurements.

The logbooks are typically accessed from Linux-based control computers located in the ISOLDE control room, in the RILIS laser laboratory, and in the new RILIS control room in building 508. A *RILIS eLogbook Posting Tool* LabVIEW program has been developed using function nodes developed on request by the RADE team to post laser status data and reference images directly from the windows-based RILIS control computers. The interface shown in Figure 43 features a text entry box and the option to attach an image via a browsing dialog or via copying a screenshot from the clipboard. With this tool, text and images obtained with REACT LabVIEW programs can be posted to the RILIS, GPS and HRS logbooks, helping to improve the communication of RILIS status data to ISOLDE users.

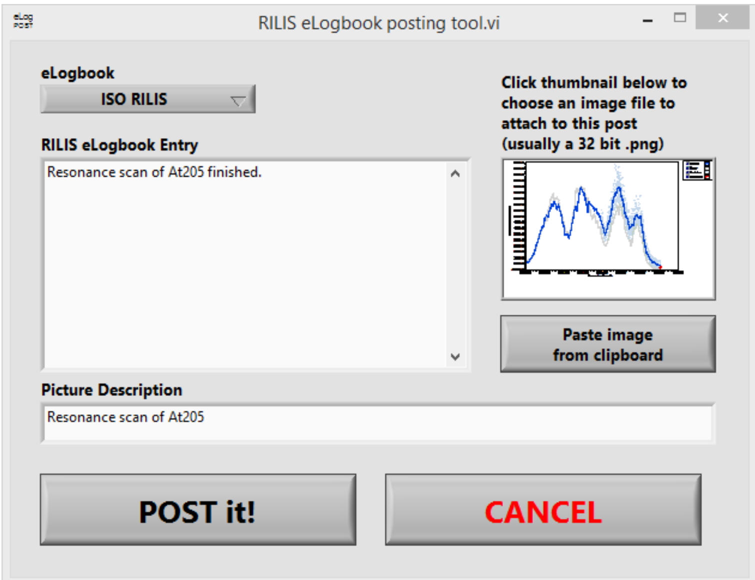

Figure 43: Front panel of the RILIS eLogbook Posting Tool.

4.5.3 RILIS Status Viewer ■ ★

Remote observation of laser parameters: A vital tool for the observation of RILIS operational parameters is the status viewer utility showing the current laser wavelengths and power values together with their setpoints. This program is configured according to the RILIS laser setup to consolidate and visualize the wavelength acquisition and reference values required for the installed ionization scheme. A typical view of the status viewer front panel is shown in Figure 44.

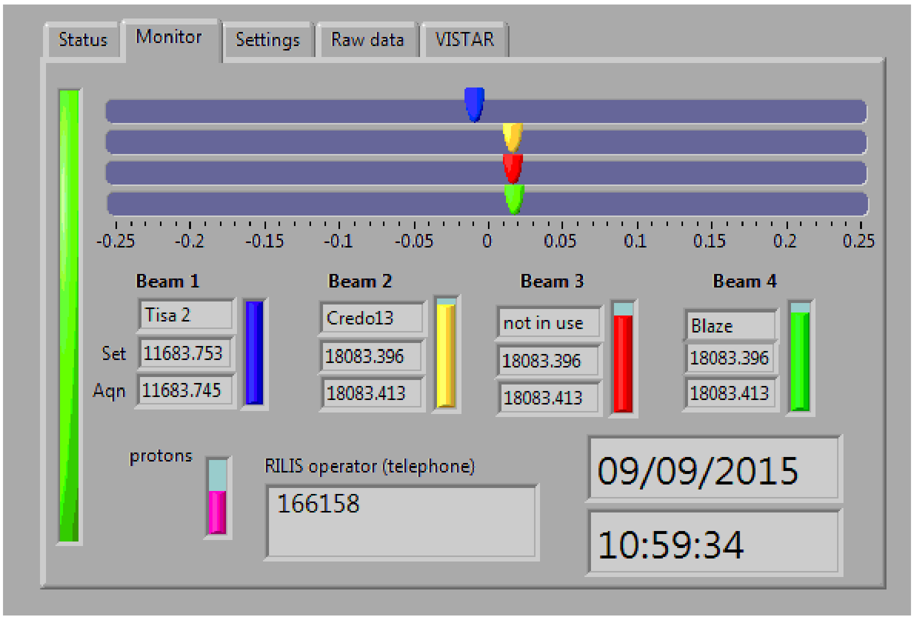

Figure 44: Screenshot of the RILIS status viewer application front panel.

Similar to the laser beam position view, a screenshot of this display is published in regular intervals to a publicly accessible website[36] that displays status information of the RILIS laser installation to be viewed remotely by RILIS operators and ISOLDE users and operators. This remote viewing option represents a necessary step towards on-call operation: Being able to view the status remotely enables the operators to estimate in advance the need for local interventions on the laser system. In addition, the status viewer aids in verifying that the current status is in accordance with reference measurements taken during the setup phase for RILIS operation. The current version of the status viewer was developed by RILIS operators and is continuously improved, making use of the shared variable infrastructure.

[36]http://riliselements.web.cern.ch/riliselements/lasers/

Long-term trend visualization: The visualization of long-term trends of the laser parameters is useful to estimate intervention times in advance and to diagnose potential problems with the laser setup. A long term visualization was developed as an application specific example to monitor the laser powers over the course of seven days, shown in Figure 45.

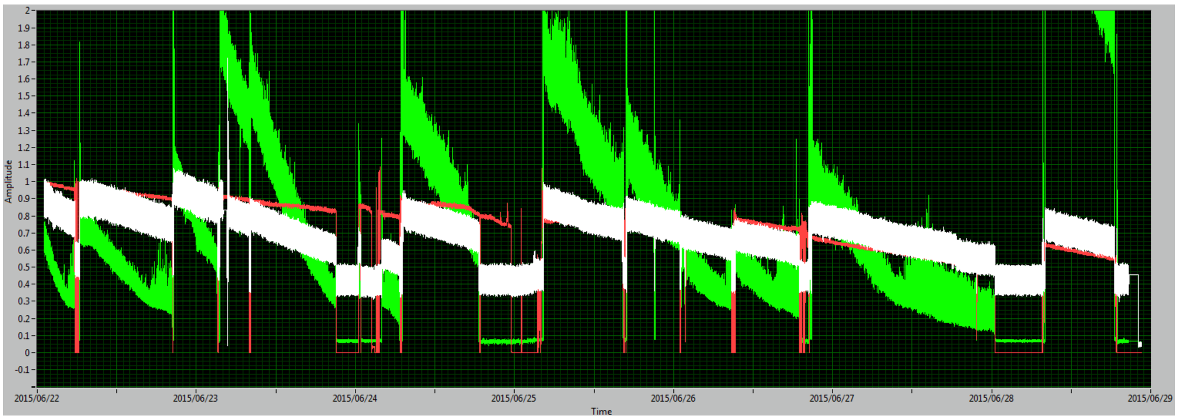

Figure 45: Screenshot of a long-term visualization showing the trend-lines of laser power values.

4.5.4 Shared Variable Viewer ★

Access to shared variables: With the availability of process values as shared variables, a set of flexible viewing and diagnostic tools is required to access and visualize the acquired values. The main development goal for these tools is to create single-purpose programs with a small footprint that can be run in multiple instances.

The use case is to have a up-to-date trend-line display of process values, such as the wavelengths or powers during setup and operation. This requirement has been met by implementing a simple shared variable viewer program that can be launched from the command line, a windows shortcut, or a batch file. With these start-up mechanisms, the URL path of the shared variable to be monitored and a role description string are passed to the program as command line arguments. The compiled program can be run in multiple instances and on multiple computers within the technical network to monitor the process values required for the current setup. This way, the RILIS operators can create a customizable 'dashboard view' on the control computers.

LabVIEW program structure: The structure of the *Shared Variable Viewer* program is illustrated in Figure 46: At launch, the command-line parameters containing the shared variable path to be monitored and the corresponding role description string are read. The shared variable viewer program makes use of the DSC module to register and process shared variable change events according the provided path. The loop iterates when a new value is received or when the user interacts with the front panel such as pressing the stop button.

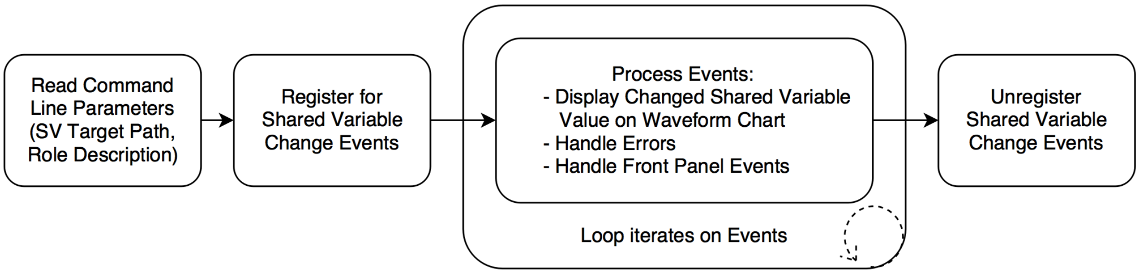

Figure 46: Program structure of the *Shared Variable Viewer* application.

4.5.5 Shared Variable Logger ★

Simplified data recording: Viewing and recording two shared variable values in relation to each other on an XY graph is a use case in ion source development and for diagnostics of the laser setup. For this purpose, a logging application was developed, offering the possibility to browse through the available shared variables, to assign values to the horizontal and vertical axis, and to start a recording for fixed time intervals. The program consists of a single loop and there is no data synchronization performed between the observed variables. For less frequently updated values, this results in multiple recordings of the same value, while for values that are changing faster than the cycle time of the XY logger, not all values are taken into account. This behaviour is acceptable for quickly logging diagnostic measurements.

4.5.6 TiSa Delay Compensator ■ ★

Setup: In order to successfully ionize the isotope of interest, the excitation laser pulses have to coincide in time within the ion source. For this purpose, a manual scan of the corresponding timing trigger channels is performed with respect to each other during the setup phase of the lasers to ensure synchronization and an optimal ionization signal.

However, while scanning the Ti:Sa laser by tilting the etalons, a change in the pulse delay with respect to the other ionization steps is inevitable. Without applying timing synchronization techniques, the ionization signal is effected up to a complete signal loss, causing erroneous measurements for ion signal ratio measurements. Manual correction of the delay value is possible from within the laser laboratory, however this is not suitable for remote operation during laser scans that can take up to 3 h. The delay shift can be compensated by adjusting the timing of the pump laser trigger signal according to the reference delay value obtained during setup time. Figure 47 illustrates the concept for correcting the timing delay between the lasers.

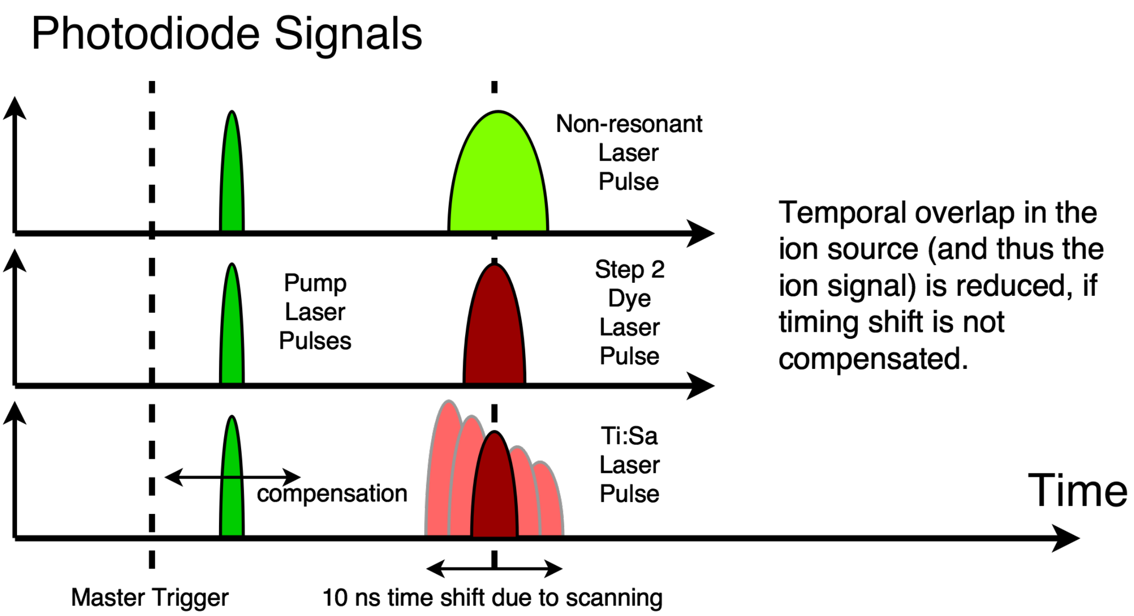

Figure 47: Illustration of the scanning Ti:Sa laser pulse delay compensation concept.

In order to automatically compensate the timing delay, a LabVIEW driver program was developed to communicate with the delay generator that triggers the pump laser of the Ti:Sa. This driver program reads the desired timing control delay from a shared variable and sends a corresponding command string to the delay generator. The implementation of this driver, described in 4.3.5, takes care that no invalid or erroneous values are sent to the hardware to avoid damaging the laser due to missing or invalid trigger signals.

The laser pulse signal was acquired by measuring the voltage across a fast photodiode, which was set up inside the Ti:Sa laser. The photodiode signal was acquired with respect to the main trigger signal by a *LeCroy* oscilloscope, thus providing a delay measurement for the laser pulse. This measurement parameter was read out by the LabVIEW driver and published as a shared variable, as described in 4.2.5. The interconnection of the REACT modules used to implement the stabilization are illustrated in Figure 48

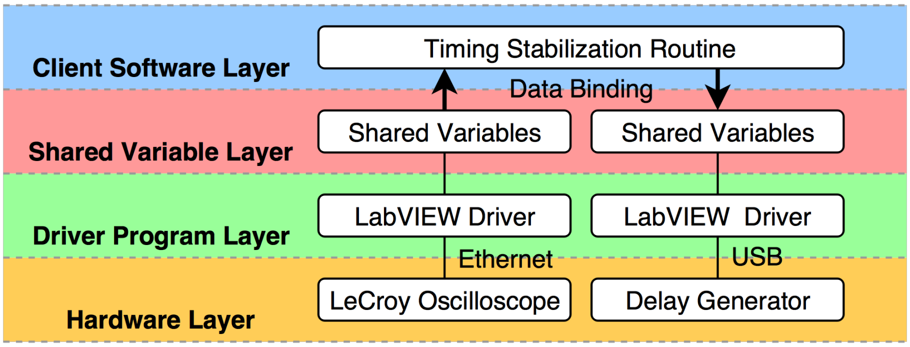

Figure 48: Interconnection of REACT components to create a timing stabilization for the scanned Ti:Sa laser.

LabVIEW implementation: The timing stabilization routine was modified from a proof-of-principle program implemented by the RILIS operators to include a visualization of the timing correction value and to implement safety thresholds to the applied timing correction. The user interface of the timing stabilization program is shown in Figure 49. Numerical indicators and controls are grouped in the left part of the front panel. The measured timing delay of the laser is averaged over 10 samples to mitigate the read-out jitter between individual laser pulses. In order to prevent setting erroneous values to the desired delay variable, a maximum difference of the delay can be specified (300 ns in this example), as well as a dead-zone where no compensation is performed (1 ns in this example). The right part of the program shows a visualization of the acquired live timing value (white), the floating average value (red) and the setpoint value (green) on the vertical axis. The array slots of the averaging routine are shown on the horizontal axis. Additional information about the modular composition of the timing stabilization is given in 5.2.3 in the next section.

4.5.7 Power Stabilization ★

Background: During standard RILIS operation, the ionization laser wavelength is kept at fixed values and the laser power is optimized to be as high as possible to allow for a maximized ionization signal. When scanning the Ti:Sa laser by moving its optomechanical elements, the resulting output power is influenced due to the changing optical properties

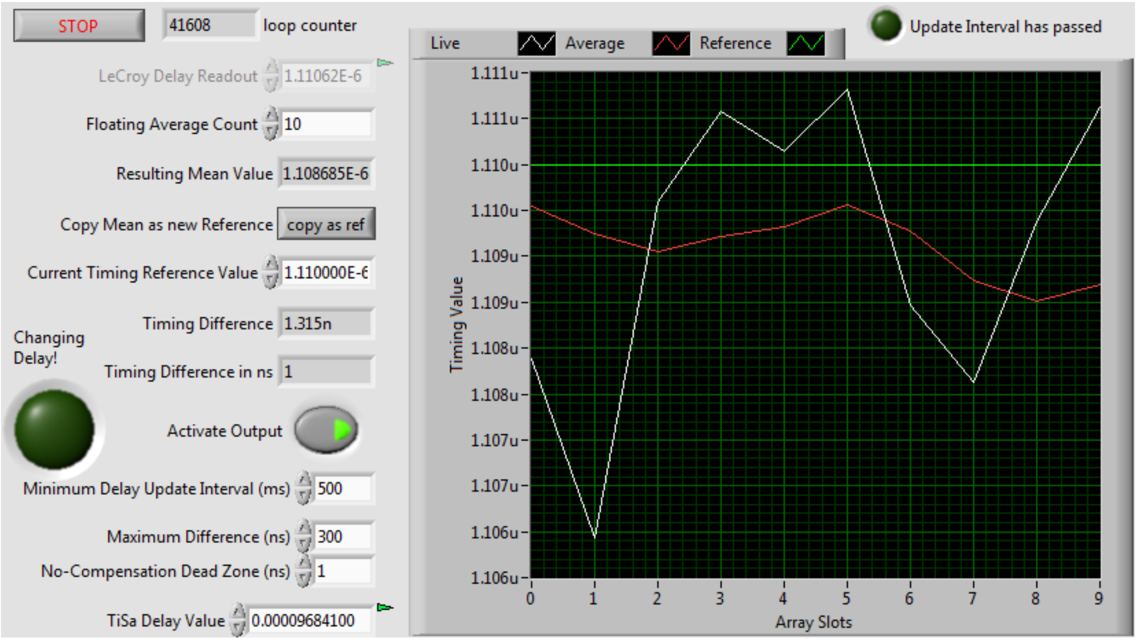

Figure 49: Front panel of the timing stabilization control program.

of the laser cavity. For the purpose of in-source laser spectroscopy, the output power of the laser has to be stabilized at a constant level over the wavelength range to be covered. An illustration of the power stabilization concept is given in Figure 50, indicating the scanning wavelength range and the corresponding *stabilized power level* in comparison with a *read-out of unstabilized power* obtained in a probing scan.

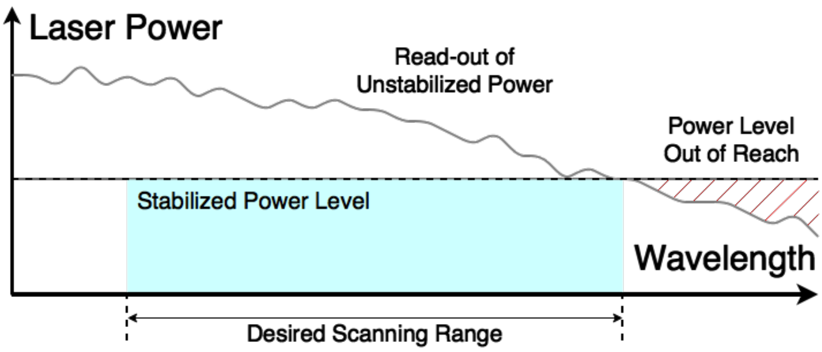

Figure 50: Illustration of the laser power attenuation concept. The stabilized power level of the laser is determined by the intersection of the limits of the desired scanning range with the read-out of the unstabilized power.

In using the REACT software modules illustrated in figure 51, a stabilization has been implemented during the course of this work to ensure a constant power level over a desired scanning range.

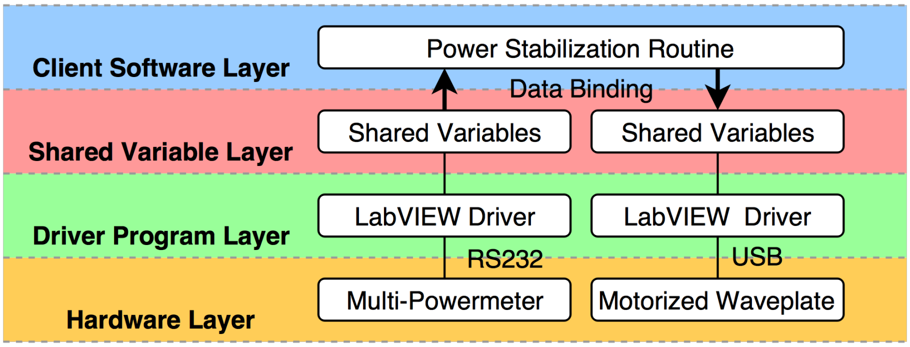

Figure 51: Interconnection of REACT components to create a power stabilization for the scanned Ti:Sa laser.

The relative laser power is measured by reading out the signal of a photodiode-based sensor that is irradiated by a 4 % pick-up of the ionization laser beam. The sensor is connected to the multi power meter which is read out by a LabVIEW driver program to publish the power measurement value as a shared variable, as described in 4.2.4. The laser power is effected by axial rotation of a motorized waveplate, thus changing polarization and consequently the conversion efficiency of the higher harmonics generation process (frequency doubling). The revolution of the waveplate is controlled by a microcontroller-based stepper driver that receives setpoint positions through a LabVIEW driver program and shared variables, described in 4.3.4. The stabilization routine program reads the power measurement values from the multi power meter and compares them with a setpoint power level set by the RILIS operator. New setpoint positions for the motorized waveplate are calculated from this comparison, creating a feedback stabilization loop to stabilize the ionization laser power.

LabVIEW implementation: The power stabilization routine consists of a modified version of the previously implemented proportional stabilization REACT module used to stabilize the laser wavelength. Due to the modular concept and the communication through shared variables, the original program module required only minor adaptations of the shared variable paths for the inputs and outputs of the feedback loop. However, the user interface of the control program shown in Figure 52 was modified to incorporate additional settings owed to the different mechanical setup. The left part of the control program combines numerical indicators and controls necessary to operate the feedback loop. The correction interval (i.e. loop iteration time), power setpoint value, proportional correction factor, and motor position can be modified with these controls. Furthermore, values for a 'Difference Threshold' and a 'Glitch Threshold' can be defined to prevent corrections on the occurrence of erroneous power meter read-outs. As the power meter read-out is a comparatively noisy control variable, the measurements are averaged over 10 samples, shown in the middle part of the control program. The right part of the program shows a visualization of the power acquisition on the vertical axis versus the motor position of the motorized waveplate on the horizontal axis. Further details of the setup and application of this power stabilization are given in the next section under 5.2.3.

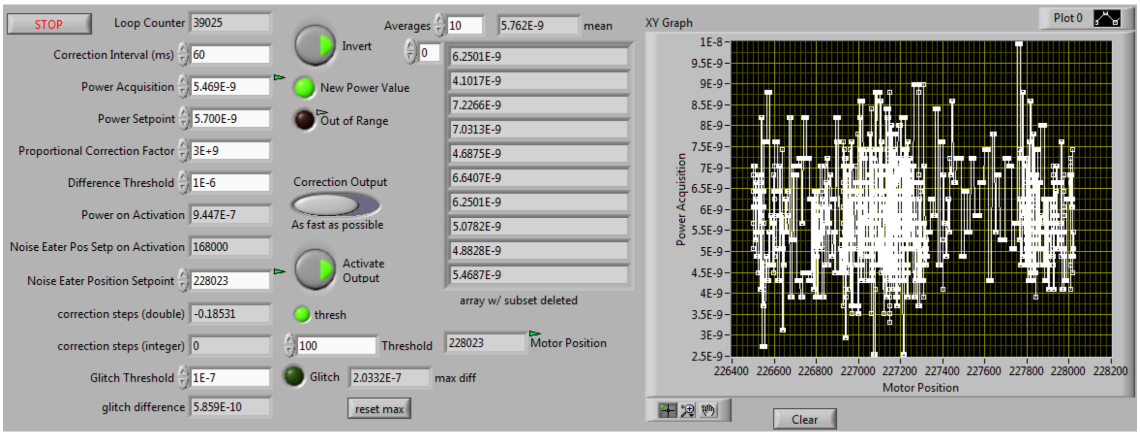

Figure 52: Front panel of the power stabilization control program.

4.5.8 VISTARS Status Control ♣

Relevant machine status information for ISOLDE users is published via 'OP Vistars' screens located in the ISOLDE control room and accessible via a website. These displays provide condensed information about key facility parameters such as proton beam information, target front-end values and the separator setup at a glance.

Representing a vital part of the information flow to the ISOLDE users, a concise publication of the current RILIS status was integrated to these displays. For this purpose, a small service program, shown in Figure 53, has been implemented, which propagates a status string to the data base server for the *Vistar* displays.

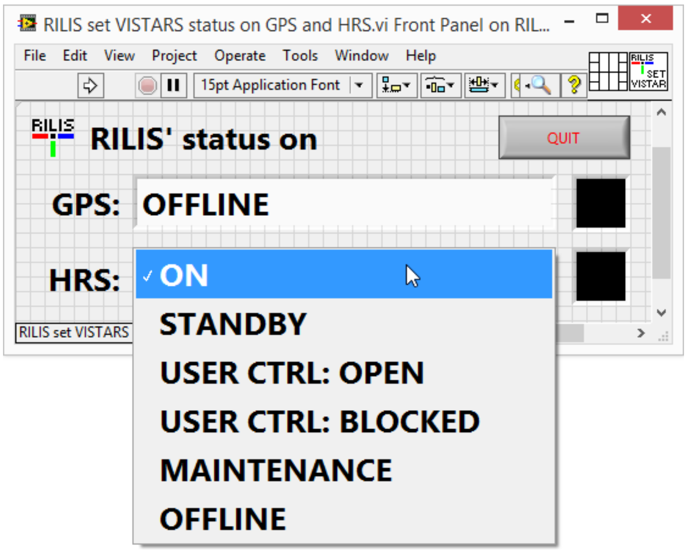

Figure 53: Front panel of the of the Vistars screen status indication program.

5 Application Examples

This section describes two application examples which make use of the REACT framework in the context of RILIS operation. The first example explains the operation and modular structure of the software used to remotely control a Ti:Sa laser in narrow linewidth operation (NB-Ti:Sa). The second example describes the interaction of REACT programs for performing in-source laser spectroscopy in collaboration with ISOLDE experiment setups from the new RILIS control room. The embedding of the application examples into the REACT framework is illustrated in Figure 54: The basis for the RILIS software development constitutes the hardware equipment, the low-level driver programs and the shared variables. Stabilization and automation routines build upon that basis to compose and support applications such as the NB-Ti:Sa control software and the RILIS data recorder. The topmost goal is the usage of these applications to operate the RILIS remotely during in-source laser spectroscopy experiments.

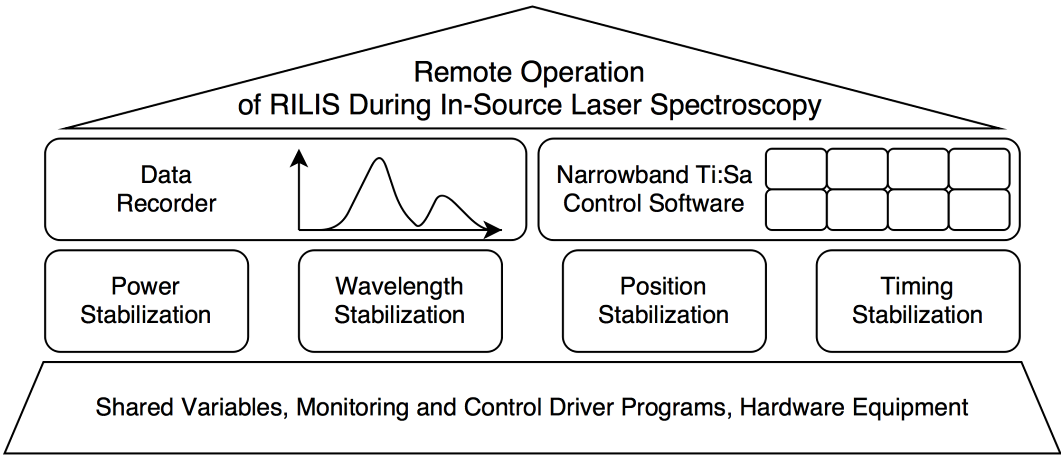

Figure 54: Structural illustration of the REACT framework. The NB-Ti:Sa control software represents a composite application which builds upon the shared variables, the low-level driver programs, and the hardware. Remote operation of the RILIS during in-source laser spectroscopy is achieved through the combined usage of programs such as the data recorder, the NB-Ti:Sa control software and stabilization routines.

5.1 Narrowband Ti:Sa Control Software

The *Narrowband Ti:Sa control software*[37] serves as an example of how the REACT framework can be used to create a composite top-level application. First, the conceptual back-

[37] LabVIEW project name: 'RILIS Remote Control'

ground for operating the RILIS Ti:Sa lasers in narrowband configuration is outlined. Second, the interconnection of existing REACT components is presented to meet the requirements for software control of the narrowband Ti:Sa. Third, the top-level application, its components and its usage are described. These sections are followed by the description of the workflow for operating the narrowband Ti:Sa control software and an evaluation of its usage.

5.1.1 Conceptual Background

Since 2011 the RILIS is equipped with a solid state laser system consisting of up to three tunable Ti:Sa lasers [14]. These lasers can be configured to enable reduced linewidth operation (0.8 - 1 GHz rather than ≈10 GHz) by inserting two etalons of different thicknesses into the laser cavity at the same time [58]. Figure 55 illustrates the dependency of the wavenumber from the etalon tilt angle.

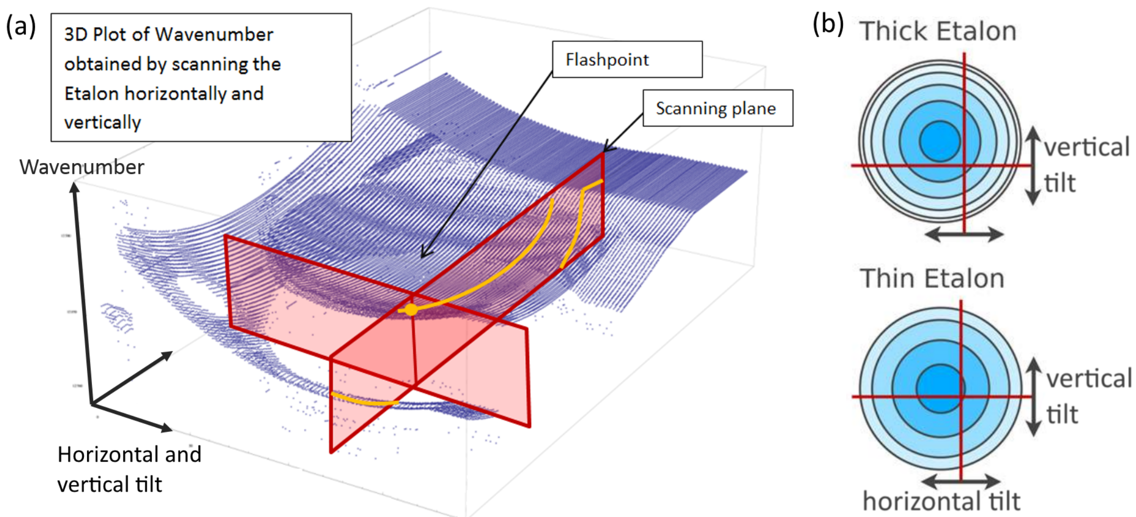

Figure 55: Illustration of a two-dimensional scan of the wavenumber versus the horizontal and vertical tilt angle of a single installed etalon on the left (a). The illustration on the right (b) sketches the wavenumber dependency from the tilt angle for two etalons of different thicknesses.

The left plot (a) shows a two-dimensional scan of the laser wavenumber versus the horizontal and vertical tilt angle of a single etalon installed in a stepper motor actuated optomechanical mount. The resulting bowl-shaped structure reveals a nonlinear relation between the wavenumber value and the tilt angle values, which becomes more evident when 'slicing' the structure along the horizontal or vertical axes by a 'scanning plane' indicated in red. The sketches on the right (b) illustrate the top views of the circular 'wavenumber value' structures which would be obtained by performing the same scan with etalons of different thicknesses. A thicker etalon would show more concentric circles of similar wavenumber values. Figure 56 illustrates the dual-etalon movement concept which is implemented by the *Narrowband Ti:Sa control software* and shows a visualization sketch of the wavenumber versus the stepper motor position of the thick etalon. The illustration represents the basis for coordinated movement of two simultaneously installed etalons (as shown in Figure 33) in the Ti:Sa laser to achieve narrowband operation.

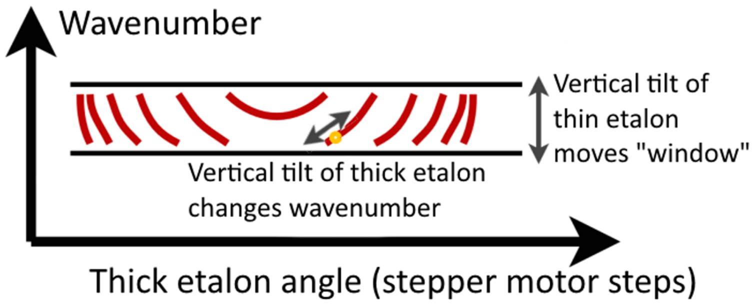

Figure 56: Illustration of the dual-etalon movement concept. Tilting the thin etalon moves a 'spectral range window' while tilting the thick etalon changes the laser wavenumber.

The thin etalon represents a 'spectral range window' which can be moved by changing the tilt angle of the corresponding optomechanical mount. At the same time, the thick etalon as to be tilted as well to achieve a wavenumber value that lies in the central region of the aforementioned 'window'. The simultaneous movement of both etalons ensures wavenumber tuning capability in narrowband mode of operation along the wavenumber lines indicated by the red lines within the illustration. The physics background of narrow linewidth operation has been explained in more detail in [10] and [58] and the description given here focuses on the implementation of the REACT concept and the usage of the composite control software, taking into account the principles of frequency selection using a dual etalon configuration.

5.1.2 REACT Interconnection

Figure 57 illustrates the system components that make up the control application for the narrowband Ti:Sa in the context of the REACT layer diagram.

For the purpose of computer controlled and automated tuning of the laser, the two etalons are installed in optomechanical mounts. The vertical tilt controls of each mount

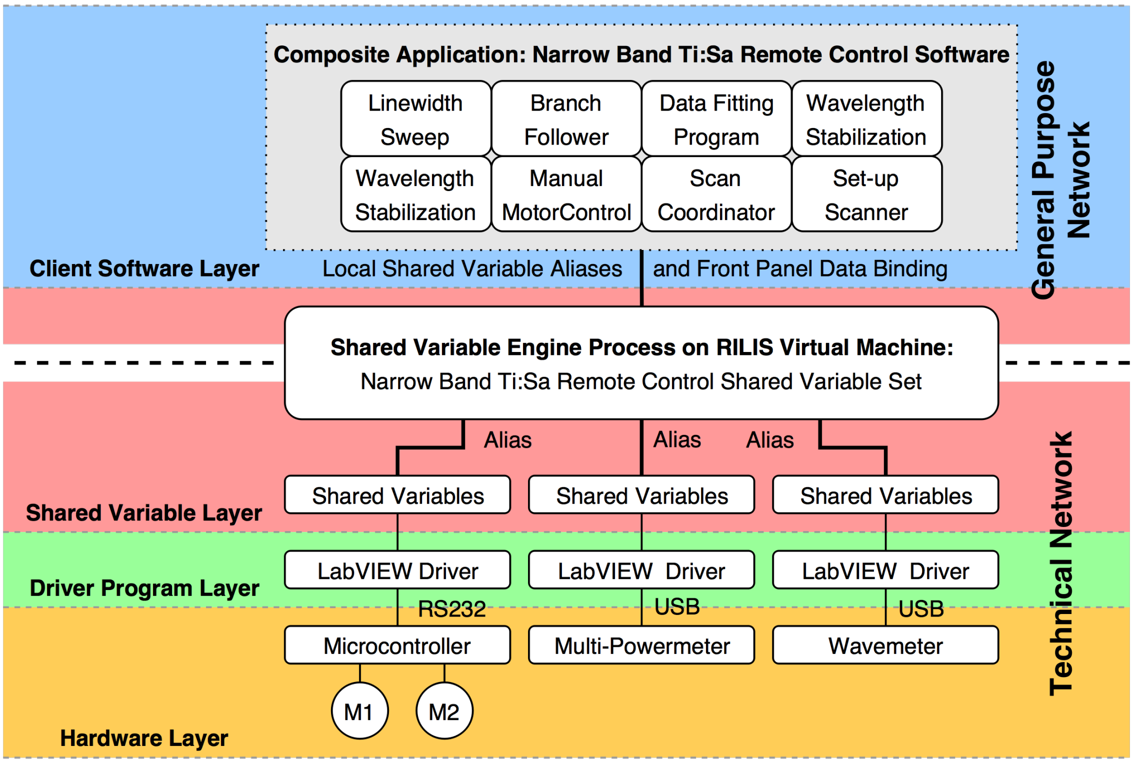

Figure 57: Illustration of the composite REACT application for controlling the RILIS narrowband Ti:Sa.

are actuated by stepper motors (M1 and M2). The stepper motors are powered by a microcontroller[38]-based stepper driver, capable of controlling up to two axes, as described in 4.3.2. Within this setup, the microcontroller is connected via the USB port to the `RILIS-SERVER` host computer and communicates using a virtual RS232 interface.

As part of the REACT driver layer, a LabVIEW driver program is used to translate the desired motor position setpoints, which are represented in the system as shared variables, into command strings to be sent to the microcontroller. The laser wavelength and power measurements are similarly published by wavemeter and power meter LabVIEW driver programs (described in 4.2.2 and 4.2.4) as shared variables.

In order to meet the requirements for remote control from the CERN *General Purpose Network* (GPN), a dedicated *Shared Variable Engine* (SVE) process has been defined on the RILIS *Virtual Machine* (VM) to host the complete library of shared variables necessary for narrowband Ti:Sa remote control. Each variable from this library is configured to connect to its low-level LabVIEW driver counterpart by specifying a corresponding

[38] Arduino [52] and EasyDriver 4.4 stepper drivers [59]

alias path. The LabVIEW programs that make up the composite top-level application use either the mechanism of front panel data binding or an alias path of a locally deployed shared variable to connect to the shared variables within the library. The usage of front panel data binding allows for changing the data binding path programmatically and for a flexible configuration of the deployment location of the shared variable target library.

Once the laser hardware is set up, adjusted to the desired wavelength and all measurement pick-offs such as wavemeter couplers and power meter heads are installed and their corresponding LabVIEW driver programs are running, further control can be assumed completely by software.

5.1.3 Top-Level Application

The narrowband Ti:Sa control software consists of a set of programs that allow for visualization and control of the laser parameters, as well as for automation capabilities. Figure 58 shows a screenshot of the main application window. Within the upper right corner of the main control window, the shared variable values for the stepper motor set-points can be directly manipulated and the current motor positions are shown. In order to view the current wavelength and power of the laser, the corresponding shared variables, provided by the respective driver readouts of the wavemeter and the power meter, are linked into the program. The main display of the control software consists of four XY graphs to visualize the laser wavelength (on the right) and the laser power (on the left) in dependence of the thick etalon motor position (on the top) and the thin etalon motor position (on the bottom). Particularly the upper right plot showing the wavenumber versus the thick etalon position corresponds to the 'scanning plane' shown in Figure 56.

With this main program, the RILIS operator can change the laser wavelength by manually changing the etalon positions and viewing the wavelength changes on the graphical displays. After the laser hardware is set up or has been changed, an initial 'characterization' process should be performed to probe the desired wavelength range and to verify that the desired scanning region can be covered. This 'characterization' process consists of acquiring and visualizing measurement values on the XY graphs to provide an indication of the dependency between wavelength and laser power with respect to the etalon positions. Additionally, the laser operator can view the spectral pattern of the laser analyzed by either the *HighFinesse* wavemeter as shown in Figure 59 in the data recorder, or by the *Atos* wavemeter, which can be observed in a separate program (*Atos pattern viewer*). The upper and lower spectral patterns on the left (a) show a multi-mode struc-

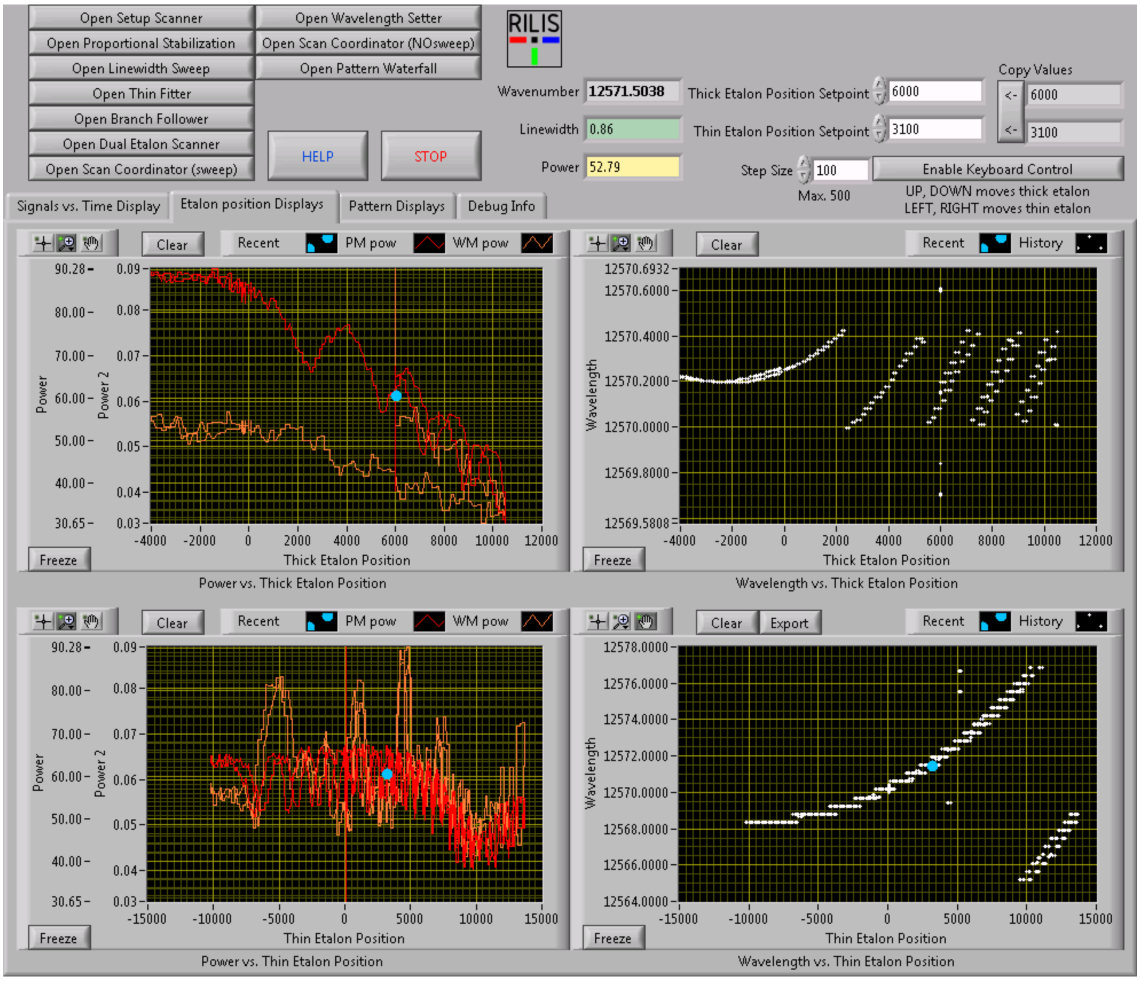

Figure 58: Illustration of the main application window used for controlling the RILIS narrowband Ti:Sa.

ture, highlighted by the red boxes, which is caused when the two etalons are not properly aligned. This structure is unsuitable for precise laser scanning of atomic resonances because the spectral impurity of the laser light will be reflected in the laser scan that is obtained through the emergence of so-called 'ghost peaks' of the ion signal. The patterns on the upper and lower right (b) show the desired, clean narrowband signal with clearly separated, equidistant fringes.

5.1.4 NBT Control Software Workflow

The typical workflow to set up the narrowband Ti:Sa control software for automatic scan operation is illustrated in Figure 60 and further described in the following paragraphs.

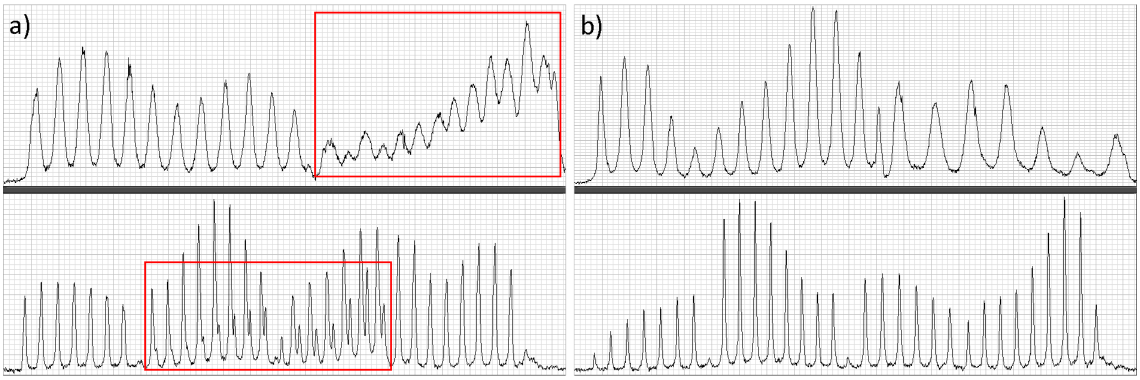

Figure 59: Screenshot of a multi-mode spectral pattern (a) and a narrowband spectral pattern (b) read-out from the wavemeter.

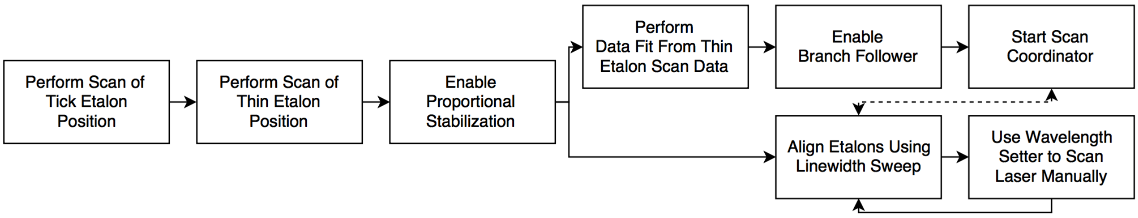

Figure 60: Illustration of the setup process of the narrowband Ti:Sa control software.

Each step in the software controlled setup process for operating the narrowband Ti:Sa laser is performed by using a single-purpose utility program within the composite application, each making use of the shared variable framework. The programs are launched by clicking the corresponding button on the upper left of the main application window, shown in Figure 58.

Thick etalon scan: The first step of the setup process consists of probing the scanning range of the optomechanical mount holding the thick etalon by manually changing the motor position shared variable over a range of maximal $\pm$ 5000 steps. This is to determine the optimal scanning range with respect to the laser power, the laser wavelength and the mechanical movement limits of the mount.

Thin etalon scan: Similar to the thick etalon scan, the scanning range of thin etalon has to be examined, yielding the additional information of the limitation of the scan range by the Lyot filter. The purpose of this scan is to accumulate measurement points on the XY plot showing the wavenumber versus the thin etalon position (lower right in the main application window). These measurement points are exported to a file by pressing the

Export button and serve as the data source for a fitting program that is used to calculate a look-up table for the movement of the thin etalon.

Proportional Stabilization Once the scanning range is verified, the laser can be set to the required wavelength and a proportional stabilization software module can be activated. This module controls the motor position of the thick etalon as the defining element for the output wavelength.

Data fit program: Starting the data fit program by pressing the *Open Thin Fitter* button on the upper left within the main program (see Figure 58) will automatically import the measurement points from the file saved during the thin etalon scan, The program will automatically perform an initial quadratic fit[39] to the data points. The laser operator can choose to include or exclude data points by marking them on the graphical display of the fit program shown in Figure 61 to obtain fit parameters that best match the desired scanning range. Plotting the measured wavenumber versus the stepper motor position shows several horizontal lines (1) which result from the scanning procedure of the thin etalon without moving the thick etalon. Each line represents the laser wavenumber determined by the thick etalon within the current 'spectral range window' of the thin etalon. The horizontal center of each line represents the region where the two etalons are properly aligned, allowing for narrowband operation. The thicker blue line (2) passes through the centers of the horizontal lines and represents the results of the fit routine, giving the optimal positions for controlling the thin etalon. The quadratic fit parameters are exported to a shared variable and are used to calculate the correct motor position for the concerted movement of the thin etalon by the *Branch Follower* utility.

Branch Follower: Depending on the set wavelength, the *Branch Follower* utility is used to automatically calculate and set the position of the thin etalon in accordance to the parameters obtained by the data fit program. This will allow the laser to be scanned within a steady wavenumber and power domain determined by the optical properties of the etalon alignment. The term 'Branch' for these scan domains originates from the projected vertical continuation of one of the red lines shown in Figure 56. The laser operator has to import the fit parameters from the shared variable and check the calculated

[39]Background information considering this nonlinear relationship can be found in [58]

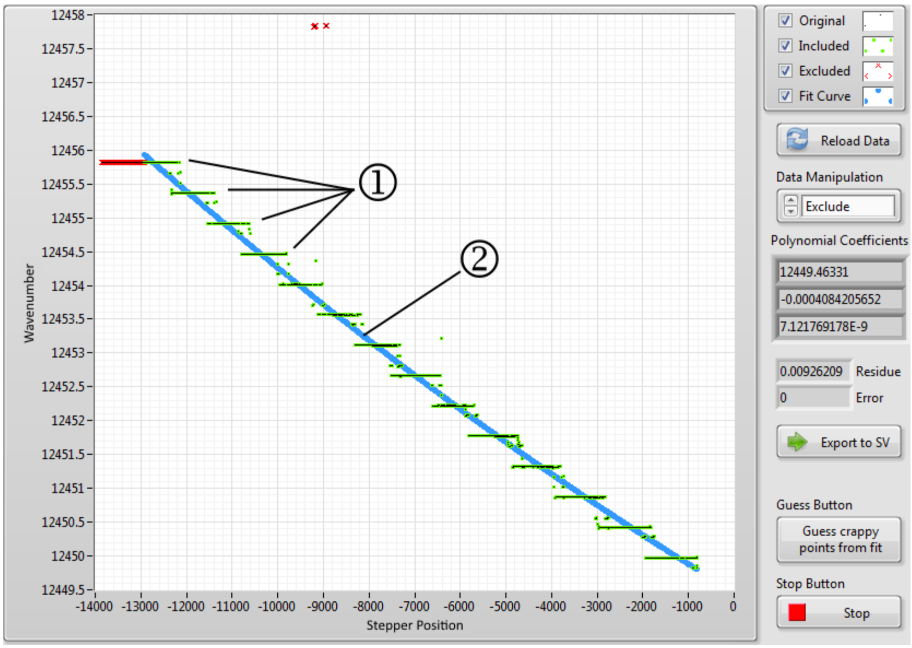

Figure 61: Screenshot of the *etalon position vs. wavenumber* data fit program within the narrowband Ti:Sa control project.

etalon position. This position value should correspond roughly[40] to the wavelength versus position relation obtained in the step 'Thin Etalon Scan'. Depending on the slope of the quadratic function, the calculated output may have to be inverted by activating the *Inv SQRT* button. Pressing the *Enable Output* button will set the corresponding stepper motor position each time a new setpoint wavelength value is received. Figure 62 shows the front panel of the *Branch Follower* utility program. The upper left indicators show general program information such as a loop counter and the stop button. The central part shows the shared variable value for the input wavelength and the currently used fit parameters. On the right, the calculated output wavelength is displayed. Buttons on the lower right allow for loading and saving the current fit parameters to a file.

Wavelength Setter: Once the narrowband Ti:Sa is set up with the *Proportional Stabilization* and the *Branch Follower* utilities running, manual changes of the setpoint wavelength shared variable can be performed by using the *Wavelength Setter* tool. This program will communicate the updated value to the both the *Proportional Stabilization* and the *Branch Follower* which will initiate the movement of the etalons. If the *Branch*

[40]There is a hysteresis of ≈ 100 steps due to the mechanical properties of the motorized optomechanical mount.

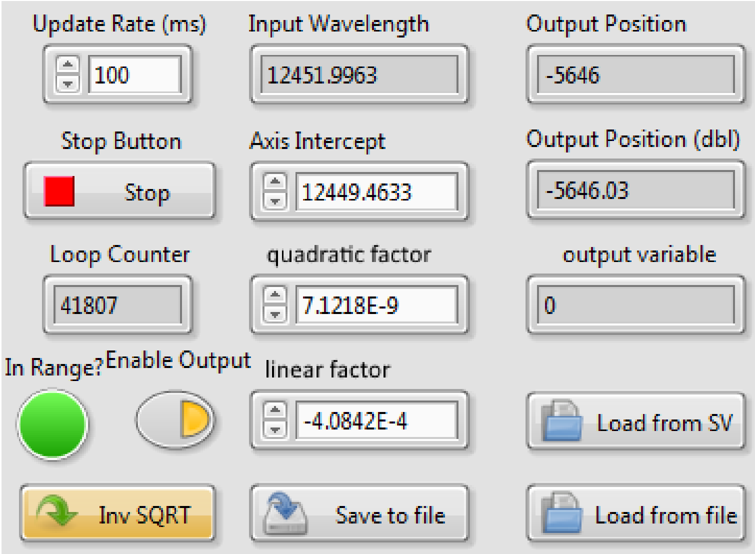

Figure 62: Screenshot of the 'Branch Follower' program within the narrowband Ti:Sa control project responsible for controlling the thin etalon tilt position.

Follower is not used, a linewidth sweep should be performed each time the setpoint wavelength is changed by $\approx 0.05\,cm^{-1}$.

Linewidth sweep program: The *Linewidth Sweep* utility can be used instead of the data fit and the *Branch Follower* program to optimize the alignment of the two etalons for narrowband operation. The thin etalon is moved from its current position until a 'mode jump', a sudden read-out value change of $\pm 0.1\,cm^{-1}$ in the wavelength measurement value, is registered. The position of this 'mode jump' is recorded and the etalon is moved in the other direction until a similar mode jump occurs. The center position between the upper and lower 'mode jump' position values is taken as the optimized thin etalon alignment position. For reliable results, the etalons should be manually pre-aligned once, avoiding wavelength jumps or a 'bad' pattern readout (see Figure 59).

Scan Coordinator: The *Scan Coordinator* utility is responsible for communication with 'external' programs such as the *RILIS Data Recorder*. When a new wavelength value is received (*double*-type shared variable `waveSet` is updated with a new value, *boolean*-type shared variable `isOK` is reset to 'FALSE' and *boolean*-type shared variable `isNew` is set to 'TRUE'), the scan coordinator, implemented as a state machine, initiates the necessary coordination steps to move the optical elements within the narrowband Ti:Sa laser to achieve the new setpoint position. Depending on the use of the *Linewidth Sweep* utility or the *Branch Follower* utility for setting the thin etalon position, two different versions of the scan coordinator are available: If the *Linewidth Sweep* utility is used, the scan coordinator automatically initiates a linewidth sweep once a new wavelength setpoint is defined in the corresponding shared variable value. With the *Branch Follower*, the thin etalon position is calculated and set directly, while the thick etalon position is adjusted by the proportional stabilization. The movement procedure is completed when the measured wavelength is within a configurable threshold (by default $0.003\,cm^{-1}$). Subsequently, the external program is notified (*boolean*-type shared variable `isNew` is reset to 'FALSE' and *boolean*-type shared variable `isOK` is set to 'TRUE') that the laser has completed moving to the new wavelength setpoint value.

5.1.5 Evaluation

As a composite application example, the narrowband Ti:Sa control software makes extensive use of the layered REACT architecture. Low-level motor drivers are directly communicating with the hardware, taking the stepping motor setpoint as inputs and reading back the actual motor position. Additional process values such as wavelength and power measurements are provided by independently running driver programs and are published as shared variables. Within the *narrowband Ti:Sa control software*, these process values are accessed within program modules that fulfill a specific task such as stabilizing the wavelength or coordinating the scan procedure. It is foreseen that additional programs may be integrated into the software at a later date by a laser operator. For example, to test different stabilization algorithms, or to perform more complex automation tasks such as an automated scanning routine. Furthermore, driver programs can be exchanged while keeping the basic shared variable interface unchanged. By deploying the shared variable library of the *narrowband Ti:Sa control software* to the RILIS virtual machine it is possible to grant access for experienced users, as was demonstrated in collaboration with the CRIS setup [60], [61], [62], [63], [64].

5.2 Remote Operation of RILIS During In-Source Laser Spectroscopy

In-source resonance ionization is the most sensitive laser spectroscopy method used by radioactive ion beam facilities and represents one of the most demanding objectives for RILIS. By varying the frequency of the tunable lasers of the RILIS while recording a signal corresponding to the ion beam intensity of the isotope of interest, a laser scan of the atomic spectral line is produced. These scans, performed along an isotope chain, give an insight into the evolution of the nuclear ground state or isomer properties such as charge radii and moments across the nuclear chart.

Collectively, the experimental installations in the ISOLDE facility house a versatile suite of ion detection systems. For a particular laser scan, the detection system is selected specifically based on the properties of the studied isotope: Abundant and clean ion beams can be detected with a Faraday cup while contaminated or low abundance, but low activity beams are best measured with the MR-ToF detector of the ISOLTRAP experiment. Alpha-decaying isotopes and their characteristic decay energy spectrum can be recorded with the 'windmill' silicon detector setup. The data acquisition system used for laser spectroscopy therefore must be universally compatible with these diverse experimental setups, which each have their own unique equipment control and measurement systems.

A further complication is the pulsed nature of isotope production at ISOLDE, as determined by the *Proton Synchrotron Booster* (PSB) driver beam supercycle, which repeats every $\approx$30 to 60 s. Therefore, stepwise and synchronized scanning of the laser frequency is required. The physics program for the measurement campaign is typically scheduled to last for about a week and it requires around-the-clock shift work involving a team from each collaborating setup. Figure 63 illustrates the principle of in-source laser spectroscopy through stepwise excitation of a valence electron (a) and shows the various participating detector setups used to perform measurements of the ion beam signal (b).

For RILIS operators, in-source laser spectroscopy work entails performing multiple laser scans, each one taking up to 3 h, which requires an extensive, redundant measurement setup and stable conditions throughout the whole measurement campaign. Similar to standard operation, crucial laser parameters have to be constantly monitored to get a comprehensive status overview. However, additional stabilization routines are required during the scans, as well as reliable communication capabilities to all involved detection stations for coordination of each measurement cycle and live data acquisition and display.

This application example describes the improved conditions for performing in-source laser spectroscopy remotely by utilizing the software components provided with the REACT framework.

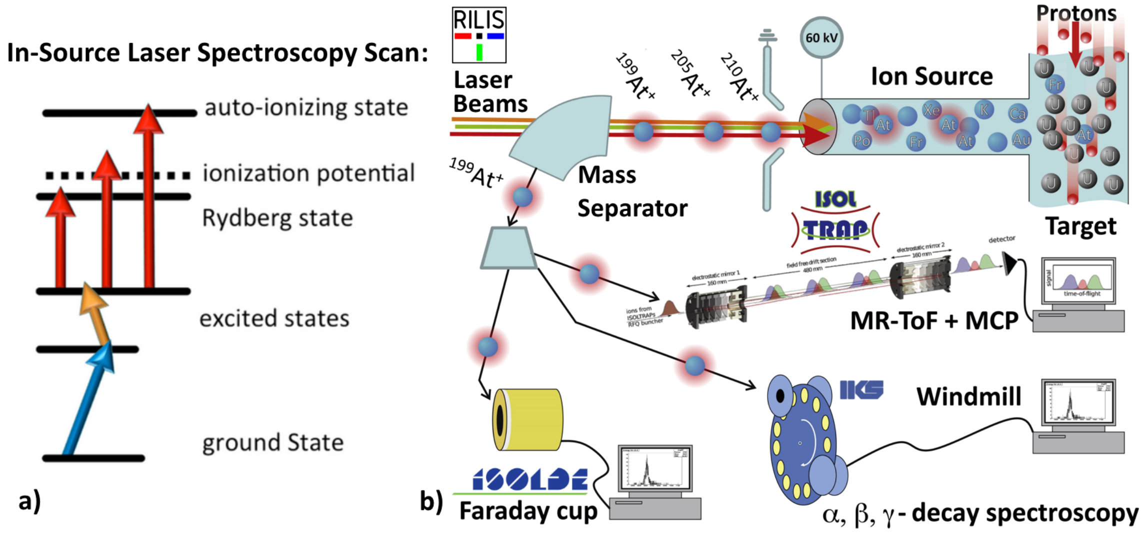

Figure 63: Schematic illustration of the in-source spectroscopy principle applied for e.g. the measurement of the ionization potential (a) and the arrangement of the experimental setups participating in in-source laser spectroscopy experiments. Images adopted an modified from [9] (a) and [20] (b).

5.2.1 REACT Components Required for In-Source Laser Spectroscopy

The RILIS laser laboratory houses the monitoring and control hardware necessary to address laser parameters such as power, wavelength, position and timing, as well as an autonomous machine protection system. The following paragraphs give a short outline of the tasks performed by the hardware or software to provide a basis for remote operation.

Power monitoring, control and stabilization: The power of the RILIS lasers is measured at setup time as a reference and in regular intervals during scheduled interventions. Continuous relative power measurements are performed by placing pick-up plates in the individual laser beams, splitting off up to 4 % of the laser light to be directed into the photodiode-based measurement heads of the multi power meter. The sensor read-out of a *position sensitive device* (PSD) at the beam observation area is recorded as a relative power measurement which is proportional to the power transmitted within the ion source.

Keeping the laser power of the scanned narrowband Ti:Sa constant over the desired scanning range is achieved through a rotating waveplate which enables the implementation of a power stabilization, described in 4.5.7. Regular interventions have to be scheduled for the dye lasers to perform a dye change due to the inevitable degradation of the laser medium after prolonged irradiation by the pump laser beam.

Wavelength monitoring, control and stabilization: The required excitation wavelengths are acquired by all three currently available wavemeters in RILIS to make use of their specific interferometer configuration and to achieve independent measurements. The WS/7 wavemeter is operated using a single channel to acquire the wavelength and linewidth measurements of the narrowband Ti:Sa laser. The WS/6 wavemeter is operated in switcher mode to acquire the wavelength measurements of all excitation laser steps involved, including a redundant measurement for the narrowband Ti:Sa. The ATOS wavemeter features four different Fizeau interferometers and provides a spectral pattern view of the narrowband Ti:Sa and an additional wavelength measurement.

Wavelength control is exerted by motorized optomechanical mounts within the Ti:Sa and the dye lasers. Scans with the narrowband Ti:Sa are enabled through the corresponding control software described previously in 5.1, which relies on the modular utilization of REACT components. Wavelength stabilization programs are included as a module within the narrowband Ti:Sa laser control program and are also available as standalone applications to be used for the dye lasers or the Ti:Sa lasers in standard 'on-call' operation.

Position monitoring, control and stabilization: The positions of the reference laser beams are acquired by network-connected CMOS cameras located at the beam observation area. The image of the beam positions is published in regular intervals to the RILIS status viewing website to allow for remote observation. The laser positions are optimized during the initial setup time using the picomotor control software described in 4.3.1. Remote control is enabled through a LabVIEW program, which mirrors the physical controller and its buttons on its front panel. A commercial beam position stabilization system[41] is currently installed in the laser laboratory, which is capable of correcting fast laser beam jitter due to air fluctuations and slow drifts caused by temperature variations over time.

Timing monitoring, control and stabilization: The timing synchronization of all ionization lasers is verified during setup time using fast photodiode signals observed on oscilloscopes within the laser laboratory. The timing of the scanned narrowband Ti:Sa laser is measured by a network-connected oscilloscope, providing a read-out for the laser pulse delay value with respect to the master clock T_0 signal which triggers all pump lasers. The pump laser pulses are synchronized by adjusting the delay value of the corresponding trigger signal channels of a delay generator. For the narrowband scanning Ti:Sa, a timing

[41] MRC Systems GmbH - "Compact" laser beam stabilization [65]

stabilization control loop was implemented and described in 4.5.6 which reads the delay measurement of the Ti:Sa laser pulse and controls the corresponding delay generator channel setting programmatically.

Machine protection and environmental sensors: An autonomous machine protection system supports the RILIS operators by providing data from environmental sensors related to the safe operation of the dye lasers, such as dye flow rate, evaporation and temperature. The system is capable of shutting down the laser system on the occurrence of warning or error conditions specified by the operators.

Data sources and communication with experiments: Ion beam current read-outs of the ISOLDE Faraday cups are provided through the *ISOLDE Device Readout* LabVIEW program. The *PSB PPP and PC Readout* and the *PSB Telegram Readout* programs provide information about the proton beam intensity and serve as a synchronization source to the individual proton pulses sent by the PSB within a supercycle. The communication with the alpha-decay spectroscopy setup requires hardware TTL trigger signals. This is handled by a TTL communicator program, which accesses a data acquisition card within the RILIS-PXI system. The laser status viewer application functions as a dashboard to summarize information of the current wavelength settings and power levels of the lasers.

5.2.2 RILIS Data Recorder

Previous related work: Flexible recording of laser parameters and measurement data is essential for ion source development and in-source laser spectroscopy work. For this purpose, a data recorder software was developed in 2014 making use of the REACT components and data sources. The motivation for developing this tool, the requirements, and implementation details are detailed in [36]. Figure 64 illustrates the requirements for the software to acquire and averaged measurement data during measurement intervals.

Application for in-source laser spectroscopy: The RILIS data recorder software was developed specifically with the application for in-source laser spectroscopy in mind and the following tasks are addressed:

- Acquisition, visualization, and recording of measurement data from shared variable sources.

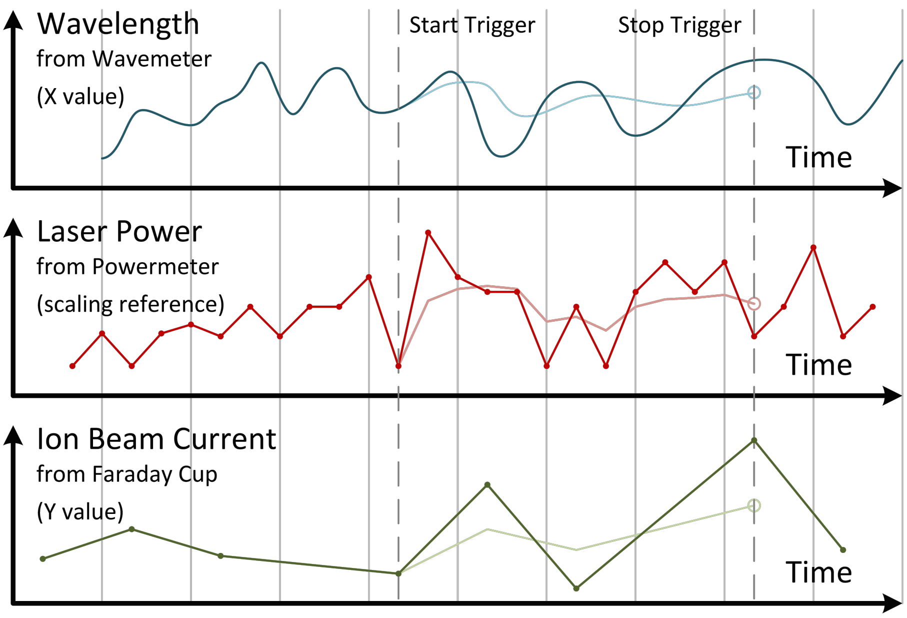

Figure 64: Illustration of the core functionality of the RILIS data recorder software: Process values from different sources are acquired and averaged for a measurement between start and stop trigger signals. [36]

- Synchronization of that data by averaging the incoming values according to selectable trigger events.
- Coordination of laser scans by controlling parallel running applications such as the narrowband Ti:Sa software.
- Data communication and coordination with collaborating experiment setups run by ISOLDE users.

The data recorder software is the main software application to be run in order to record the laser parameters provided by the hardware communication programs. During the setup process, the software is configured to access and accumulate relevant data by specifying the paths to the shared variables that need to be recorded. The recording process consists of averaging the incoming data between start and stop trigger signals. Figure 65 shows the available trigger settings that control the data acquisition process on the left part of the front panel. Scan-related settings to identify the generated data files can be entered in the upper central part of the settings panel. The lower central part provides an sketch description of the scanning routine based on the proton pulses.

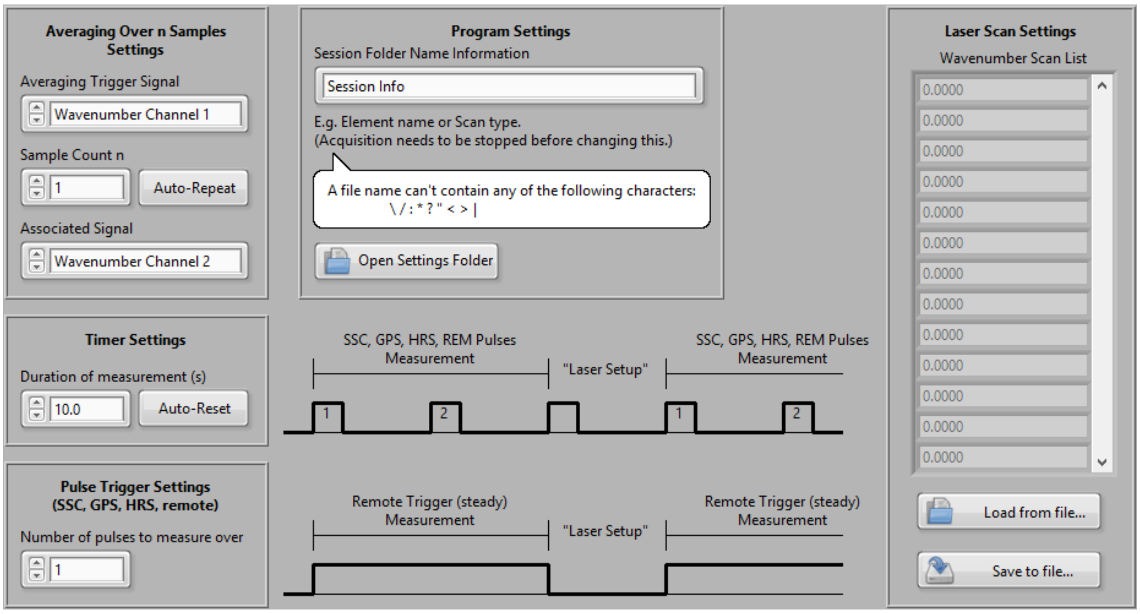

Figure 65: Configuration options for triggering the data acquisition within the RILIS data recorder.

Step-wise laser scans can be performed in conjunction with the *narrowband Ti:Sa control software*[42]. After loading a pre-defined 'Wavenumber Scan List' on the right side of the settings tab of the data recorder, it is possible to start the automated data acquisition and laser scan process. During in-source laser spectroscopy, this process typically takes 1.5 h to 3 h, depending on the selected triggers, the abundance of the targeted isotope, and the scanning wavelength range to cover. Due to the degree of automation and stabilization provided through the REACT software, typically no further interaction with the laser system is required during the measurement process.

In visualizing the measurement data, the RILIS operators can get an immediate feedback of the scan process and perform an assessment of the data quality. Figure 66 shows an example data plot of a reference laser scan of ^{198}Hg. The data acquisition can be preset to record measurement values from different sources such as from collaborating experiment setups or from the ISOLDE Faraday cups. This is beneficial for performing regular reference measurements to verify stable ion beam conditions and for coordinating the shift work between the participating teams.

Communication and coordination with the ISOLDE user experiment setups is realized either through the use of shared variables or through the use of hardware TTL signals.

[42]Described in 5.1

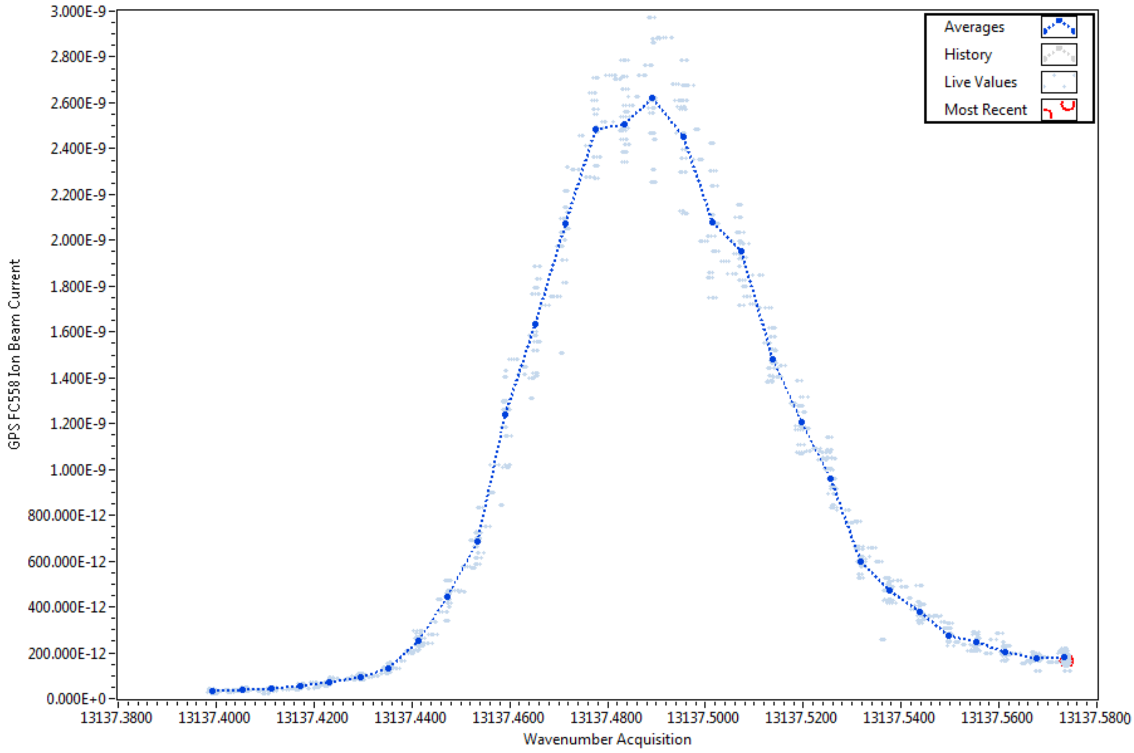

Figure 66: Raw data plot of a completed reference laser scan of ^{198}Hg. The scan was obtained by a stepwise change of the laser frequency and automatically averaging measurement values over number of proton pulses set by the RILIS operator.

When collaborating with the ISOLTRAP setup, the RILIS data recorder is responsible for coordinating and synchronizing the measurement process according to the proton pulse structure present in the supercycle. When collaborating with the alpha-decay 'windmill' setup, the laser scan is coordinated by TTL signals generated by the detector setup due to its required hardware synchronization with the supercycle.

5.2.3 Developments for Remote Operation

Commissioning the new control room: With the completion of the new ISOLDE office building 508 in spring 2015, a new control room for RILIS was available outside the ISOLDE hall *Radiation Protection - Supervised Area*. During the course of this work, this room was commissioned to function as an office space, meeting room and foremost as a remote control room to supervise the RILIS laser installation. For this purpose, the following IT and communication infrastructure, pictured in Figure 67, was installed:

(1) A dedicated control computer, connected to the CERN technical network, is equipped

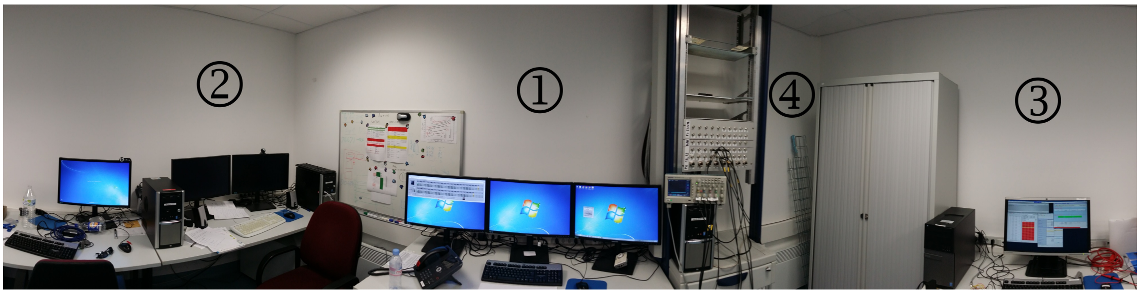

Figure 67: Panoramic view of the control computers and communication infrastructure in the new RILIS control room.

with three screens to function as a remote workstation for displaying all relevant laser parameters. This workstation serves as a customizable control console which runs top-level LabVIEW programs such as the RILIS data recorder and the narrowband Ti:Sa control program. Additional programs such as the timing and power stabilization programs are also run on this computer, communicating to the equipment driver programs in the RILIS laser room via shared variables.

② Two additional computers, connected to the CERN general purpose network, are equipped with up to two screens to function as office computers and data analysis workstations. The data taken during in-source laser spectroscopy experiments is saved to a network drive, remotely accessible by RILIS operators. With the two additional internet connected computers available, data analysis can be performed simultaneously during the experiment. Additionally, users from collaborating experiments can use the GPN computers to remote connect to their setups and view their experiment status in context with RILIS data.

③ A computer with the CERN scientific Linux operating system is connected to the technical network and serves as an ISOLDE control workstation. This workstation mirrors the essential monitoring and control applications of the Java-based ISOLDE controls framework. This comprehensive IT infrastructure ensures that no physical access to the ISOLDE hall or the RILIS laboratory is needed during operation unless a specific hardware problem is encountered.

④ Signal cables suitable for TTL connections[43] and signal cables suitable for network

[43] 20 channels to the RILIS laser room, 8 channels to the ISOLDE data acquisition room and 15 channels to the new ISOLDE control room

connections[44] have been installed to enable the transfer of trigger signals and network data. This allows for immediate monitoring of electrical signals outside of the laser room and improves the connectivity options to the ISOLDE physics network and to the user experiment setups.

With the new RILIS control room equipped for experiment work it is possible to remotely monitor and control the laser installation, as well as essential ISOLDE beam instrumentation parameters in an ergonomic work environment. The need for operator presence in the laser room is reduced through the implementation of automated stabilization programs that are supervised from this new control room.

Power stabilization: After setting up the hardware and software components to facilitate power stabilization[45], a reference scan of the 'power tuning curve', shown in Figure 68, can be obtained by manually incrementing the stepper motor position shared variable for the waveplate[46].

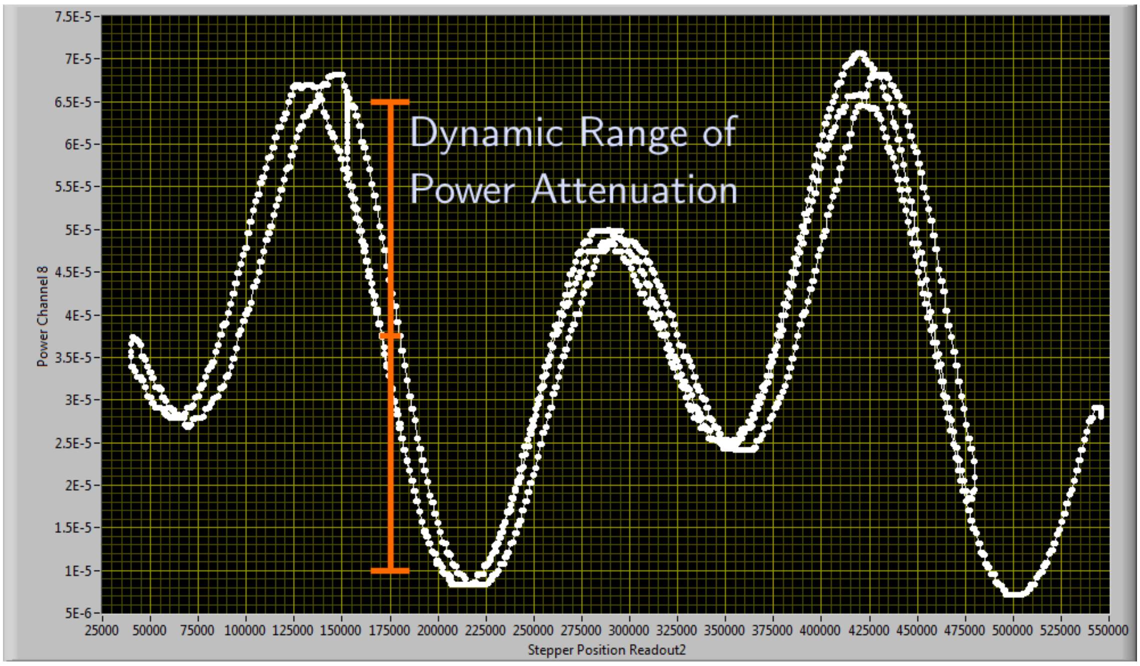

Figure 68: Tuning curve of the power stabilization setup.

[44] 8 channels (category 7 certified) to the RILIS laser room
[45] The hardware setup and program control is described in 4.5.7
[46] The diagnostic plots shown here were created with the *Shared Variable Logger* 'top level utility' described previously in section 4.5.5

The recorded power signal 'Power Channel 8' in W is displayed versus the stepper motor steps 'Stepper Position Readout2'. The motor position was incremented and decremented for ≈ 500 000 steps in order to achieve at least one full rotation of the waveplate for the characterization of the dynamic range of the setup. A full rotation of the waveplate is completed after ≈ 275 000 motor steps and yields a power reduction of approximately a factor of 6.5. Reduction values outside this range can be achieved by applying fixed neutral density filters in addition to this setup, resulting in a vertical offset of the indicated curve. Multiple plots shown in Figure 68 visualize the mechanical hysteresis of the stepper motor and the optomechanical mount. Despite this issue, optimal power stabilization can be achieved within the dynamic range indicated, spanning roughly 50 000 steps.

Result: A screenshot of the recorded power signal 'Power Channel 8' in W versus the scan wavelength 'Wavenumber Channel 1' in cm^{-1} is given in Figure 69. The plots denoted with (1) in the top part indicate a gradient loss of the laser power of up to 50 % within the desired scanning range if no stabilization is applied. The middle plot denoted with (2) indicates the stabilized power value over the same scanning range. Plot (3) on the bottom indicates the 'reference' zero level of the power value to correspond to the actual zero value.

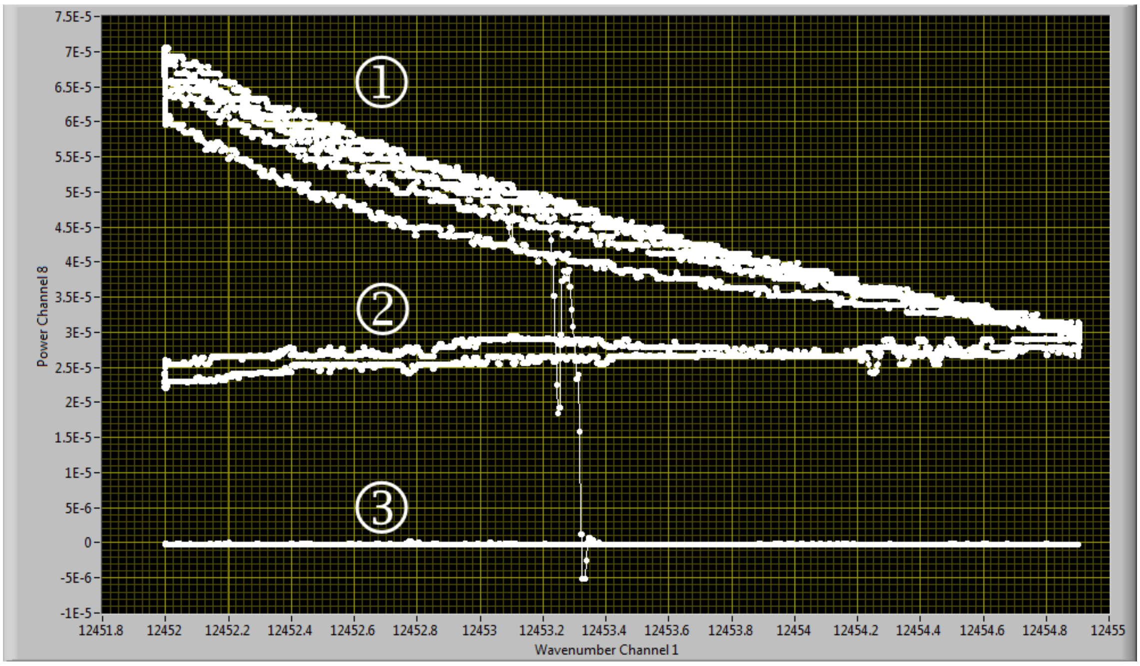

Figure 69: Plots of laser power versus laser wavelength with the power stabilization disabled (1), enabled (2), and a zero reference measurement (3).

During post-analysis of the data gained in previous in-source laser spectroscopy runs, discrepancies in the signal ratios of the investigated spectral lines have been identified with respect to theoretical predictions. With the power stabilization system installed, the power fluctuations could be reduced and verified, while the experiment was in progress. Under power-stabilized conditions, laser scans were obtained with relative spectral line intensities matching the theoretical predictions. Furthermore, the fact that the required hardware for the power stabilization could be quickly installed and the corresponding software could be reused highlights the effectiveness of the modular concept of the REACT system.

Timing Stabilization: The power stabilization application makes use of the delay measurement variable obtained from the *LeCroy* oscilloscope[47], a timing reference measurement value (i.e. the setpoint) obtained during the setup phase of the RILIS lasers, and the timing control variable sent to the timing delay generator[48]. In a feedback stabilization loop, the acquired delay measurement value is compared to the setpoint reference. A correction value is then calculated and written to the timing control variable of the trigger generator driver to adjust the timing accordingly.

Result: Figure 70 shows a screenshot of the recorded timing signal 'Parameter 1' versus the scan wavelength. The orange plots indicate a timing shift of up to 10 ns within the desired scanning range, taken during laser scans without any compensation[49]. The blue plot indicates a stabilized timing value over the same scanning range.

Similar to the results of the power stabilization, the fluctuations in the measurement signal could be reduced and compared to the theoretical predictions for each particular scan. No extra hardware was required to enable the timing control by communicating with the delay generator. The REACT software was extended by implementing a corresponding device driver and a feedback stabilization loop to address this task immediately during the setup phase of the experiment.

5.2.4 Evaluation

The software components available in the REACT framework provide remote access to the equipment within the RILIS laser laboratory through the CERN technical network. For each of the four primary monitoring and control domains power, wavelength, position, and

[47] Implementation details are given in 4.2.5
[48] The corresponding control program is described in 4.5.6
[49] The plots shown here were created with the *RILIS Data Recorder 2014* described in section [36]

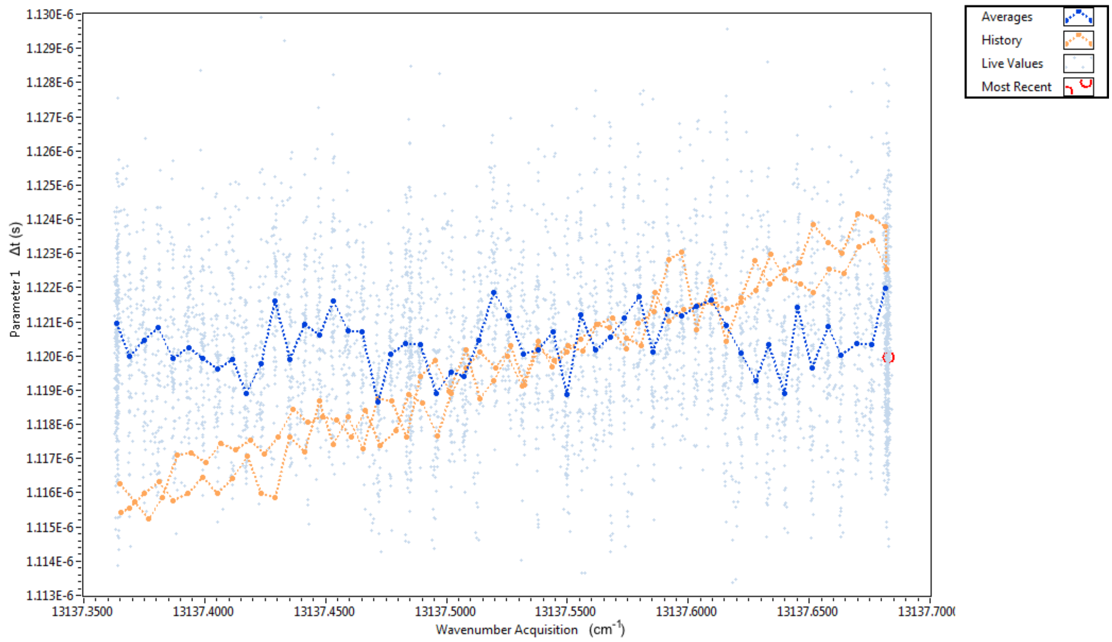

Figure 70: Plot of the recorded timing delay while scanning the Ti:Sa laser. The orange line depicts the uncompensated timing value while the blue line shows the stabilized value.

timing, dedicated LabVIEW drivers have been developed to communicate the laser beam instrumentation hardware and to expose the corresponding process values as remotely accessible shared variables. Additional parameters such as data received from the PSB, ISOLDE ion beam instrumentation data, and measurement data from collaborating user experiment setups were read out and visualized by corresponding programs.

The user interfaces of monitoring and control programs needed for RILIS operation allow the operators to customize a 'dash board' view suitable for the current mode of operation. By the use of network shared variables, process data is transferred to and from the computers in the RILIS laser laboratory that run the driver programs necessary for communicating with the hardware equipment. Software components that perform automated power and timing stabilization were developed on demand during the experiment, further reducing the need for interventions in the laser laboratory. The modular programs of the REACT framework were used to perform in-source laser spectroscopy measurement campaigns in May 2015 (Mercury) [66] and April 2015 (Gold) [67] completely remotely from the new control room outside of the ISOLDE experimental hall.

6 Conclusion

In the course of this thesis work, the *RILIS Equipment Acquisition and Control Toolset* (REACT) software collection has been documented and developed further towards a distributed monitoring, control, and data acquisition system. This development work focused on implementing stabilization programs for the laser parameters power, wavelength (dye lasers), and timing, extending the REACT system to meet the requirement of stabilized laser beam parameters during remotely operated in-source laser spectroscopy experiments. The Ti:Sa laser wavelength was scanned and stabilized by the use of the *Narrowband Ti:Sa Control Software* while the *RILIS Data Recorder* software was used to acquire measurement data of all available laser parameters, to coordinate the laser scans, and to communicate with collaborating experiment setups. The software components of the REACT system enabled RILIS operators to conduct two in-source laser spectroscopy experiments[50], probing the hyperfine structures and isotopes shifts of mercury and gold isotopes, remotely from the newly commissioned RILIS control room outside the radiation supervised area of the ISOLDE hall.

The reduced need for manual intervention through remote monitoring and control programs, as well as the increased stability of measurement parameters have improved both the quality and the quantity of the data that were obtained. While performing more than 160 automated scans over the course of 20 days in 24/7 shift operation, fluctuations in wavelength, timing and power of the laser beams could be reduced to provide steady measurement conditions, while providing a live data overview to the operators and users on shift. This mode of operation enabled the participating physicists to perform preliminary analyses of live data and compare them to the theoretical predictions during the process of data taking. The facilitation of remote operation outside of the laser laboratory has reduced the health and safety risks to the RILIS operators, as well as enabled a more comfortable working environment during the stressful and time-pressured experimental period.

However, the introduction of an open and sufficiently flexible hardware and software system entails also new challenges. Due to the increased amount of parameters that can be monitored and acquired, the overall setup time for RILIS operation is extended by the time required to ensure the read-out and control software is configured correctly for

[50] In April and in May 2015

remote access. This is compensated by the time gained through automation routines running in parallel and the reduced need for manual correction and optimization of the laser parameters. The expandability of the software framework by the operators who may wish to implement new modules on demand introduces a paradigm shift from purely being responsible for the experimental setup towards working more interdisciplinary and investing time into software development.

The requirements for the REACT system development towards a remote monitoring and control system have been accomplished by providing an extended software tool-set, suitable for observing and manipulating crucial RILIS laser parameters from outside the laser laboratory. On-call operation, introduced in 2014 for selected ionization schemes, has become the standard mode of RILIS operation in 2015 by making use of web-based monitoring programs and an independently running machine protection system. In-source laser spectroscopy experiments, as one of the most challenging objectives in RILIS operation, can now be performed remotely in close collaboration with ISOLDE users and in an ergonomic work environment.

7 Outlook

The current implementation state of the REACT framework allows the transition from manual, local operation towards remote monitoring, control, and data acquisition. The automation programs that have been developed have saved time during on-line operation and provided improved working conditions, especially during in-source laser spectroscopy operation. This approach can be pursued further through the continual development of the REACT framework in addressing the following future improvements:

- **Simplified configuration:** In the current implementation state, many programs used by RILIS operators have been developed as a proof-of-concept to solve a specific task, such as reading from hardware devices and displaying or recording values from arbitrary shared variables. In order to increase their flexibility and ease of use, the programs could be refactored towards better code reuse, as well as to make use of external configuration files which can be edited by the operators without having to change source code. As an example, lightweight programs such as the *Shared Variable Viewer* utility[51] make use of command line parameters to set their internal configuration to be run in multiple instances.

- **Usability improvements:** Currently, most read-out values are recorded or visualized using their shared variable path information for identification. However, when visualizing values of arbitrary shared variables in the context of the laser setup, the association with a human-readable information string is recommended to increase the overall usability of the system. For example, a laser wavenumber could be read out from Channel 3 of the WS/7 Wavemeter on the RILIS-SERVER using the path '\\RILIS-SERVER\HighFinessse WS7 Shared Variables\Wavenumber Channel 3'. In the context of the laser setup applied for an experiment, this value could be associated with the corresponding optical excitation scheme information such as 'second excitation step'. This information string should be easily configurable and included into the top-level visualization programs.

- **Refactoring and maintenance:** Future developments should focus on improved error handling and increased use of design patterns where applicable to simplify maintenance and expandability of the software. Many currently existing driver programs consist of a single-purpose loop, which is sufficient for simple read-out tasks

[51] Description in section 4.5.4

but lack the flexibility to integrate additional tasks related to inter-application communication. The *Actor Framework* [68] provided by National Instruments represents a design pattern which was specifically developed to simplify object oriented development of applications which focus on message based inter-process communication between program modules. The RILIS data acquisition application could benefit from a rework using the Actor Framework in terms of improved maintainability and expandability.

- **Additional hardware and software implementation:** As has been documented in section 4, the REACT software components can cover a large area of crucial monitoring and control tasks for RILIS. However, lower priority tasks such as constant timing monitoring or environmental monitoring tasks such as chiller read-outs are still to be addressed. Also, the acquisition of additional hardware or the extension of the functionality of top-level applications needs to be considered for future developments.

References

[1] CERN. Archives of the Isotope Separator On Line-DEtector, ISOLDE. http://library.web.cern.ch/archives/CERN_archive/guide/experimental_physics/SC/isaisolde. Accessed: 2015-05-27.

[2] I. website. History. http://isolde.web.cern.ch/history. Accessed: 2015-09-01.

[3] C. Department. CERN accelerator complex image. http://te-dep-epc.web.cern.ch/te-dep-epc/machines/pagesources/Cern-Accelerator-Complex.jpg. Accessed: 2015-05-27.

[4] CERN. The accelerator complex. http://home.web.cern.ch/about/accelerators. Accessed: 2015-05-27.

[5] E. Kugler. The ISOLDE facility. *Hyperfine Interactions*, **129**, 1-4, 23–42 (2000). ISSN 0304-3843. DOI:10.1023/A:1012603025802.

[6] Krib. Schema of the "Isotope Separator On Line DEvice" (ISOLDE) at CERN. https://commons.wikimedia.org/wiki/File:ISOLDE_Schema.png. Accessed: 2015-08-23.

[7] V. N. Fedosseev, Y. Kudryavtsev and V. I. Mishin. Resonance laser ionization of atoms for nuclear physics. *Physica Scripta*, **85**, 5, 058104 (2012).

[8] B. A. Marsh. Resonance ionization laser ion sources for on-line isotope separators. *Review of Scientific Instruments*, **85**, 2, 02B923 (2014). DOI:http://dx.doi.org/10.1063/1.4858015.

[9] S. Rothe. RILIS at ISOLDE - motivation for RILIS. http://rilis.web.cern.ch/motivation-rilis. Accessed: 2015-06-12.

[10] S. Rothe, K. D. A. Wendt and W. Nörtershäuser. *An all-solid state laser system for the laser ion source RILIS and in-source laser spectroscopy of astatine at ISOLDE/CERN*. D.Phil. thesis, Mainz U. (2012). Presented 24 Sep 2012.

[11] B. Marsh, L.-E. Berg, D. Fedorov, V. Fedosseev, O. Launila, M. Lindroos, R. Losito, F. Österdahl, T. Pauchard, I. Pohjalainen, U. Sassenberg, M. Seliverstov, A. Sjödin and G. Tranströmer. The isolde rilis pump

laser upgrade and the laris laboratory. *Hyperfine Interactions*, **196**, 1-3, 129–141 (2010). ISSN 0304-3843. DOI:10.1007/s10751-010-0168-5.

[12] V. N. Fedosseev, L.-E. Berg, D. V. Fedorov, D. Fink, O. J. Launila, R. Losito, B. A. Marsh, R. E. Rossel, S. Rothe, M. D. Seliverstov, A. M. Sjödin and K. D. A. Wendt. Upgrade of the resonance ionization laser ion source at ISOLDE on-line isotope separation facility: New lasers and new ion beams. *Review of Scientific Instruments*, **83**, 2, 02A903 (2012). DOI:http://dx.doi.org/10.1063/1.3662206.

[13] V. Fedosseev, L.-E. Berg, N. Lebas, O. Launila, M. Lindroos, R. Losito, B. Marsh, F. Österdahl, T. Pauchard, G. Tranströmer and J. Vannesjö. ISOLDE RILIS: New beams, new facilities. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, **266**, 19–20, 4378 – 4382 (2008). ISSN 0168-583X. Proceedings of the XVth International Conference on Electromagnetic Isotope Separators and Techniques Related to their Applications. DOI:http://dx.doi.org/10.1016/j.nimb.2008.05.038.

[14] S. Rothe, B. A. Marsh, C. Mattolat, V. N. Fedosseev and K. Wendt. A complementary laser system for ISOLDE RILIS. *Journal of Physics: Conference Series*, **312**, 5, 052020 (2011).

[15] S. R. et al. Laser ion beam production at CERN-ISOLDE: new features - more possibilities. *EMIS 2015 Proceedings* (submitted).

[16] R. E. Rossel, D. Richter, K. Wendt and S. Rothe. *Programming of the Wavelength Stabilization for a Titanium:Sapphire Laser using LabVIEW and Implementation into the CERN ISOLDE RILIS Measurement System*. Bachelor's Thesis, Hochschule RheinMain, Wiesbaden, (and Johannes Gutenberg-Universität Mainz) (2011). Presented 15 Feb 2012.

[17] R. Rossel, V. Fedosseev, B. Marsh, D. Richter, S. Rothe and K. Wendt. Data acquisition, remote control and equipment monitoring for ISOLDE RILIS. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, **317, Part B**, 0, 557 – 560 (2013). ISSN 0168-583X. XVIth International Conference on ElectroMagnetic Isotope Separators and Techniques Related to their Applications, December 2–7, 2012 at Matsue, Japan. DOI:http://dx.doi.org/10.1016/j.nimb.2013.05.048.

[18] D. Fink, S. Richter, B. Bastin, K. Blaum, R. Catherall, T. Cocolios, D. Fedorov, V. Fedosseev, K. Flanagan, L. Ghys, A. Gottberg, N. Imai, T. Kron, N. Lecesne, K. Lynch, B. Marsh, T. Mendonca, D. Pauwels, E. Rapisarda, J. Ramos, R. Rossel, S. Rothe, M. Seliverstov, M. Sjödin, T. Stora, C. V. Beveren and K. Wendt. First application of the laser ion source and trap (LIST) for on-line experiments at ISOLDE. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, **317, Part B**, 417 – 421 (2013). ISSN 0168-583X. XVIth International Conference on ElectroMagnetic Isotope Separators and Techniques Related to their Applications, December 2–7, 2012 at Matsue, Japan. DOI:http://dx.doi.org/10.1016/j.nimb.2013.06.039.

[19] T. D. G. et al. Laser resonance ionization inside the FEBIAD: Blurring the boundaries between ion sources. *EMIS 2015 Proceedings* (submitted).

[20] B. Marsh, B. Andel, A. Andreyev, S. Antalic, D. Atanasov, A. Barzakh, B. Bastin, C. Borgmann, L. Capponi, T. Cocolios, T. D. Goodacre, M. Dehairs, X. Derkx, H. D. Witte, D. Fedorov, V. Fedosseev, G. Focker, D. Fink, K. Flanagan, S. Franchoo, L. Ghys, M. Huyse, N. Imai, Z. Kalaninova, U. Köster, S. Kreim, N. Kesteloot, Y. Kudryavtsev, J. Lane, N. Lecesne, V. Liberati, D. Lunney, K. Lynch, V. Manea, P. Molkanov, T. Nicol, D. Pauwels, L. Popescu, D. Radulov, E. Rapisarda, M. Rosenbusch, R. Rossel, S. Rothe, L. Schweikhard, M. Seliverstov, S. Sels, A. Sjödin, V. Truesdale, C. V. Beveren, P. V. Duppen, K. Wendt, F. Wienholtz, R. Wolf and S. Zemlyanoy. New developments of the in-source spectroscopy method at RILIS/ISOLDE. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, **317, Part B**, 550 – 556 (2013). ISSN 0168-583X. XVIth International Conference on ElectroMagnetic Isotope Separators and Techniques Related to their Applications, December 2–7, 2012 at Matsue, Japan. DOI:http://dx.doi.org/10.1016/j.nimb.2013.07.070.

[21] R. Billen, E. L. Casado and M. Van den Eynden. Use of Java in the CERN Accelerator Environment - A CERN Technical White Paper. Technical Report SL-Note-99-001-CO, CERN, Geneva (1999).

[22] W. Lavrijsen. PyROOT: A python – ROOT bridge. http://wlav.web.cern.ch/wlav/pyroot/. Accessed: 2015-09-07.

[23] R. de Groote. CRISTALCLEAR - python DAQ and laser control software for the CRIS experiment. https://github.com/rubendegroote/CRISTALCLEAR. Accessed: 2015-09-07.

[24] CERN. ROOT data analysis framework. https://root.cern.ch/drupal/. Accessed: 2015-09-02.

[25] A. Dworak, F. Ehm, P. Charrue and W. Sliwinski. The new CERN controls middleware. *Journal of Physics: Conference Series*, **396**, 1, 012017 (2012).

[26] A. Masi and R. Losito. LHC Collimators Low Level Control System. *IEEE Trans. Nucl. Sci.*, **55**, 333–340 (2008).

[27] CERN. EN-ICE-MTA mandate. https://wikis.web.cern.ch/wikis/display/EN/MTA+Mandate. Accessed: 2015-08-26.

[28] P. Blume. *The LabVIEW Style Book*. National Instruments Virtual Instrumentation Series. Pearson Education (2007). ISBN 9780132797276.

[29] J. Travis and J. Kring. *LabVIEW for Everyone: Graphical Programming Made Easy and Fun (3rd Edition) (National Instruments Virtual Instrumentation Series)*. Prentice Hall PTR, Upper Saddle River, NJ, USA (2006). ISBN 0131856723.

[30] N. Instruments. Using the LabVIEW shared variable. http://www.ni.com/white-paper/4679/en/. Accessed: 2015-08-21.

[31] N. Instruments. LabVIEW Datalogging and Supervisory Control (DSC) module. http://www.ni.com/labview/labviewdsc/. Accessed: 2015-09-02.

[32] CERN. About RADE. http://rade-drupal.web.cern.ch/. Accessed: 2015-07-29.

[33] O. O. Andreassen, D. Kudryavtsev, A. Raimondo, A. Rijllart, V. Shaipov and R. Sorokoletov. The LabVIEW RADE Framework Distributed Architecture. *Conf. Proc.*, **C111010**, CERN-ATS-Note-2011-116 TECH (2011).

[34] M. Arruat, L. Fernandez, S. Jackson, F. Locci, J.-L. Nougaret, M. Peryt, A. Radeva, M. Sobczak and M. V. Eynden. Front-end software architecture. In *ICALEPCS*, volume 7, (page 310) (2007).

[35] T. Bress. *Effective LabVIEW Programming*. National Technology & Science Press (2013). ISBN 9781934891087.

[36] R. E. Rossel, D. Richter and S. Rothe. Network Distributed Data Acquisition, Storage, and Graphical Live Display Software for a Laser Ion Source at CERN. Technical Report CERN-OPEN-2015-005, CERN, Geneva (2014).

[37] N. Instruments. Advanced LabVIEW debugging: Profiling VI execution with the LabVIEW desktop execution trace toolkit. http://www.ni.com/white-paper/8083/en/. Accessed: 2015-08-21.

[38] N. Instruments. Web publishing tool dialog box. http://zone.ni.com/reference/en-XX/help/371361J-01/lvdialog/web_publishing_tool_db/. Accessed: 2015-08-21.

[39] N. Instruments. Remote panels in LabVIEW – distributed application development. http://www.ni.com/tutorial/4791/en/. Accessed: 2015-09-08.

[40] HighFinesse. HighFinesse High Precision Wavelength Meters. http://www.highfinesse.com/en/wavelengthmeter/28/high-precision-wavelength-meter. Accessed: 2015-08-24.

[41] *Wavelength Meter WS/7 User Manual*.

[42] N. Instruments. National instruments VISA. https://www.ni.com/visa/. Accessed: 2015-08-21.

[43] S. Rothe. Preparation of negative ion beams for the determination of the electron affinity of polonium and astatine by laser photodetachment. Technical Report CERN-INTC-2013-037. INTC-I-148, CERN, Geneva (2013). Topics: Atomic Physics and Physical Chemistry Requested beams: Po and At.

[44] Keithley. 6487 Picoammeter Voltage Source. http://www.keithley.com/products/dcac/sensitive/lowcurrent?mn=6487. Accessed: 2015-08-25.

[45] CERN. Controls configuration service. https://ccdb.cern.ch/. Accessed: 2015-08-26.

[46] EN-ICE-MTA. RIO. http://rade-drupal.web.cern.ch/rio. Accessed: 2015-08-26.

[47] N. Instruments. NI PXIe-6363 X series data acquisition. http://sine.ni.com/nips/cds/view/p/lang/en/nid/207417. Accessed: 2015-08-26.

[48] B. Marsh. Position sensitive detector read-out proof-of-principle implementation.

[49] R. E. Rossel. RILIS machine protection specification. Technical Report EDMS 1541808, CERN, Geneva (2012).

[50] N. Instruments. NI CompactRIO. http://www.ni.com/compactrio/. Accessed: 2015-08-27.

[51] Newport. Picomotor piezo linear actuators. http://www.newport.com/Picomotor-Piezo-Linear-Actuators/853235/1033/info.aspx. Accessed: 2015-08-27.

[52] Arduino. Homepage. https://www.arduino.cc/. Accessed: 2015-08-27.

[53] S. L. GmbH. Pulsed lasers: Credo dye. http://www.sirah.com/laser/pulsed-lasers/credo-dye. Accessed: 2015-08-25.

[54] Newport. Variable attenuator/beamsplitters. http://www.newport.com/Manually-Variable-Polarizing-Cube-Beamsplitters/579565/1033/info.aspx. Accessed: 2015-08-28.

[55] N. Instruments. Logging data with national instruments citadel. http://www.ni.com/white-paper/6579/en/. Accessed: 2015-07-31.

[56] N. Instruments. NI DIAdem. http://www.ni.com/diadem/. Accessed: 2015-09-09.

[57] S. Rothe. Laser ion source mapper proof-of-principle implementation.

[58] S. Rothe, V. Fedosseev, T. Kron, B. Marsh, R. Rossel and K. Wendt. Narrow linewidth operation of the RILIS Titanium:Sapphire laser at ISOLDE/CERN.

Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms, **317, Part B**, 561 – 564 (2013). ISSN 0168-583X. XVIth International Conference on ElectroMagnetic Isotope Separators and Techniques Related to their Applications, December 2–7, 2012 at Matsue, Japan. DOI:http://dx.doi.org/10.1016/j.nimb.2013.08.058.

[59] B. Schmalz. Easy driver stepper motor driver - an open source hardware stepper motor drive project. `http://www.schmalzhaus.com/EasyDriver/index.html`. Accessed: 2015-09-01.

[60] T. Cocolios, H. A. Suradi, J. Billowes, I. Budinčević, R. de Groote, S. D. Schepper, V. Fedosseev, K. Flanagan, S. Franchoo, R. G. Ruiz, H. Heylen, F. L. Blanc, K. Lynch, B. Marsh, P. Mason, G. Neyens, J. Papuga, T. Procter, M. Rajabali, R. Rossel, S. Rothe, G. Simpson, A. Smith, I. Strashnov, H. Stroke, D. Verney, P. Walker, K. Wendt and R. Wood. The Collinear Resonance Ionization Spectroscopy (CRIS) experimental setup at CERN-ISOLDE . *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, **317, Part B**, 565 – 569 (2013). ISSN 0168-583X. XVIth International Conference on ElectroMagnetic Isotope Separators and Techniques Related to their Applications, December 2–7, 2012 at Matsue, Japan. DOI:http://dx.doi.org/10.1016/j.nimb.2013.05.088.

[61] Lynch, K.M., Billowes, J., Bissell, M.L., Budincevic, I., Cocolios, T.E., De Groote, R.P., De Schepper, S., Fedosseev, V.N., Flanagan, K.T., Franchoo, S., Garcia Ruiz, R.F., Heylen, H., Marsh, B.A., Mason, P.J.R., Neyens, G., Procter, T.J., Rossel, R.E., Rothe, S., Simpson, G.S., Smith, A.J., Strashnov, I., Stroke, H.H., Walker, P.M., Wendt, K.D.A. and Wood, R.T. CRIS: A new method in isomeric beam production. *EPJ Web of Conferences*, **63**, 01007 (2013). DOI:10.1051/epjconf/20136301007.

[62] K. T. Flanagan, K. M. Lynch, J. Billowes, M. L. Bissell, I. Budinčević, T. E. Cocolios, R. P. de Groote, S. De Schepper, V. N. Fedosseev, S. Franchoo, R. F. Garcia Ruiz, H. Heylen, B. A. Marsh, G. Neyens, T. J. Procter, R. E. Rossel, S. Rothe, I. Strashnov, H. H. Stroke and K. D. A. Wendt. Collinear resonance ionization spectroscopy

of neutron-deficient francium isotopes. *Phys. Rev. Lett.*, **111**, 212501 (2013). DOI:10.1103/PhysRevLett.111.212501.

[63] K. M. Lynch, J. Billowes, M. L. Bissell, I. Budinčević, T. E. Cocolios, R. P. De Groote, S. De Schepper, V. N. Fedosseev, K. T. Flanagan, S. Franchoo, R. F. Garcia Ruiz, H. Heylen, B. A. Marsh, G. Neyens, T. J. Procter, R. E. Rossel, S. Rothe, I. Strashnov, H. H. Stroke and K. D. A. Wendt. Decay-assisted laser spectroscopy of neutron-deficient francium. *Phys. Rev. X*, **4**, 011055 (2014). DOI:10.1103/PhysRevX.4.011055.

[64] K. Flanagan, J. Billowes, M. Bissell, I. Budinčević, T. Cocolios, R. de Groote, S. De Schepper, V. Fedosseev, S. Franchoo, R. Garcia Ruiz, H. Heylen, K. Lynch, B. Marsh, G. Neyens, T. Procter, R. Rossel, S. Rothe, I. Strashnov, H. Stroke and K. Wendt. First results from the CRIS experiment. *Hyperfine Interactions*, **227**, 1-3, 131–137 (2014). ISSN 0304-3843. DOI:10.1007/s10751-013-0988-1.

[65] MRC Systems GmbH. Active Laser Beam Stabilization Model "Compact". `http://www.mrc-systems.de/deutsch/products/beamalignment.html#Compact`. Accessed: 2015-09-16.

[66] L. P. Gaffney, T. Day Goodacre, A. Andreyev, M. Seliverstov, N. Althubiti, B. Andel, S. Antalic, D. Atanasov, A. E. Barzakh, K. Blaum, J. Billowes, T. E. Cocolios, J. Cubiss, G. Farooq-Smith, D. V. Fedorov, V. N. Fedosseev, R. Ferrer, K. T. Flanagan, L. Ghys, C. Granados, A. Gottberg, F. Herfurth, M. Huyse, D. G. Jenkins, D. Kisler, S. Kreim, T. Kron, Y. Kudryavtsev, D. Lunney, K. M. Lynch, B. A. Marsh, V. Manea, T. M. Mendonca, P. L. Molkanov, D. Neidherr, R. Raabe, J. P. Ramos, S. Raeder, E. Rapisarda, M. Rosenbusch, R. E. Rossel, S. Rothe, L. Schweikhard, S. Sels, T. Stora, I. Tsekhanovich, C. Van Beveren, P. Van Duppen, M. Veinhard, R. Wadsworth, A. Welker, F. Wienholtz, K. Wendt, G. L. Wilson, S. Witkins, R. Wolf and K. Zuber. In-source laser spectroscopy of mercury isotopes. Technical Report CERN-INTC-2014-060. INTC-P-424, CERN, Geneva (2014).

[67] A. Andreyev and A. Barzakh. *beta* -delayed fission, laser spectroscopy and shape-coexistence studies with astatine beams (Part I); Delineating the island of deformation in the light gold It isotopes by means of laser spectroscopy (Part II). Technical Report CERN-INTC-2013-002. INTC-P-319-ADD-1, CERN, Geneva (2013).

[68] N. Instruments. Actor framework. `https://decibel.ni.com/content/groups/actor-framework-2011`. Accessed: 2015-08-21.

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A Glossary of Terms

Etalon	Thin plate of transmissive material
RS-232	Recommended Standard (also: Radio Sector) 232, out-dated but common designation for the EIA-232 serial communication computer interface
Wavenumber	The Wavenumber of a Laser is the reciprocal value of the Wavelength. It is usually denoted in cm^{-1} (inverse centimeters.)
Baud rate	Symbols per second i.e. line state changes per second. In binary transmissions, as used in the RS-232 interface, the bit rate corresponds to the baud rate.

B Abbreviation Index

CCD	**C**harge-**c**oupled **D**evice
CCDB	**C**ontrols **C**onfiguration **D**ata **B**rowser
CERN	**C**onseil **E**uropéen pour la **R**echerche **N**ucléaire
CMOS	**C**omplementary **m**etal-**o**xide-**s**emiconductor
CMW	**C**ontrols **M**iddle**w**are
DAQ	**D**ata **A**c**q**uisition
DLL	**D**ynamic **L**ink **L**ibrary
DSC	**D**atalogging and **S**upervisory **C**ontrol
DSO	**D**igital **S**torage **O**scilloscope
ECE	**E**quipment **C**ontrols and **E**lectronics
EN	**En**gineering department
EIA-232	**E**lectronic **I**ndustries **A**ssociation **232**
FCU	**F**requency **C**onversion **U**nit
FESA	**F**ront **E**nd **S**oftware **A**rchitecture
GPN	**G**eneral **P**urpose **N**etwork
GUI	**G**raphical **U**ser **I**nterface
GPIB	**G**eneral **P**urpose **I**nterface **B**us
HCI	**H**uman-**C**omputer **I**nteraction
HG	**H**armonics **G**eneration
HMI	**H**uman-**M**achine **I**nterface
ICE	**I**ndustrial **C**ontrols & **E**ngineering
IDE	**I**ntegrated **D**evelopment **E**nvironment
INTC	**I**SOLDE and **N**eutron **T**ime-of-Flight experiments **C**ommittee
IP	**I**nternet **P**rotocol
IR	**I**nfra**r**ed
ISOLDE	**I**sotope **S**eparator **O**n **L**ine **DE**vice (formerly: **DE**tector)
ISST	**I**ntensity **S**patial **S**pectral **T**emporal
JAPC	**J**ava **API** for **P**arameter **C**ontrol
LabVIEW	**Lab**oratory **V**irtual **I**nstrumentation **E**ngineering **W**orkbench
LARIS	**LA**ser **R**esonance **I**onization **S**pectroscopy
LARISSA	**LA**ser **R**esonanz **I**onisation für **S**pektroskopie in **S**elektiven **A**nwendungen
LHC	**L**arge **H**adron **C**ollider

LIST	**L**aser **I**on **S**ource and **T**rap
LOI	**L**etter **o**f **I**ntent
LP	**L**asers and **P**hotocathodes section
M2M	**M**achine **to** **M**achine communication
MR-ToF	**m**ulti-**r**eflectron **t**ime-**o**f-**f**light
NB	**N**arrow **B**andwidth (i.e. narrow linewidth)
Nd:YAG	**N**eodymium-**d**oped **Y**ttrium **A**luminium **G**arnet
NI	**N**ational **I**nstruments
NI-DSM	**N**ational **I**nstruments **D**istributed **S**ystem **M**anager
MTA	**M**easurement **T**est **A**nalysis
OLE	**O**bject **L**inking and **E**mbedding
OPC	**O**pen **P**latform **C**ommunications (formerly: **OLE** for **P**rocess **C**ontrol)
PC	**P**roton **C**urrent
PCI	**P**eripheral **C**omponent **I**nterconnect
PLC	**P**rogrammable **L**ogic **C**ontroller
PoE	**P**ower-**o**ver-**E**thernet
PPP	**P**rotons **p**er **P**ulse
PSB	**P**roton **S**ynchrotron **B**ooster
PSD	**P**osition **S**ensitive **D**etector
PSP	**P**ublish and **S**ubscribe **P**rotocol
PVSS	**P**rozeß-**V**isualisierungs- und **S**teuerungs-**S**oftware
PXI	**P**CI e**X**tensions for **I**nstrumentation
RADE	**R**apid **A**pplication **D**evelopment **E**nvironment
REACT	**R**ILIS **E**quipment **A**cquisition and **C**ontrol **T**oolset
RILIS	**R**esonance **I**onization **L**aser **I**on **S**ource
RIO	**R**ADE **I**nput/**O**utput
RMPS	**R**ILIS **M**achine **P**rotection **S**ystem
RS-232	**R**ecommended **S**tandard **232**
SCADA	**S**upervisory **C**ontrol **a**nd **D**ata **A**cquisition
SHG	**S**econd **H**armonics **G**eneration
STI	**S**ources, **T**argets and **I**nteractions group
SVE	**S**hared **V**ariable **E**ngine
THG	**T**hird **H**armonics **G**eneration
Ti:Sa	**Ti**tanium:**Sa**pphire

TISD	**T**arget and **I**on **S**ource **D**evelopment
TN	**T**echnical **N**etwork
TTL	**T**ransistor **T**ransistor **L**ogic
UV	**U**ltra**v**iolet
URL	**U**niform **R**esource **L**ocator
USB	**U**niversal **S**erial **B**us
VI	**V**irtual **I**nstrument
VISA	**V**irtual **I**nstrument **S**oftware **A**rchitecture
VLC	**V**ideo**LAN** **C**lient
VM	**V**irtual **M**achine
WinCC OA	**Win**dows **C**ontrol **C**enter **O**pen **A**rchitecture