ASDEX Upgrade CODAC Overview

Gerhard Raupp, Karl Behler, Helmut Blank, Annedore Buhler, Reinhard Drube, Klaus Engelhardt, Christoph Fuchs, Andreas Lohs, Roland Merkel, Gregor Neu, Horst Eixenberger, Gerold Schramm, Wolfgang Treutterer, Dieter Zasche, Thomas Zehetbauer, and ASDEX Upgrade Team

Max-Planck Institut fuer Plasmaphysik, EURATOM Association, Boltzmannstrasse 2, D-85748 Garching, Germany

Corresponding author:
Dr. Gerhard Raupp
Max-Planck Institut fuer Plasmaphysik, EURATOM Association
Boltzmannstrasse 2
D-85748 Garching
Germany
Tel **49 89 3299 1715
Fax **49 89 3299 1313
gerhard.raupp@ipp.mpg.de

Abstract

ASDEX Upgrade´s CODAC system integrates about 70 plant systems for diagnostics, magnets, heating and fuelling, vessel and protection for operation. Plant and CODAC systems base on workstations with fast serial real-time data sampling, industrial PCs and PLCs, connected through standardized networks for exchange of time and real-time process data, protection information, audio/video streams and arbitrary data. The experiment cycle defines the procedure to develop the physics program. Pulse schedules are compiled as a distributed task among plant engineers and session leader. Prior to pulse execution plant data are exchanged and consistency validated by a central configuration server. Pulses are executed by a real-time network of plant systems. Control has been designed for critical applications, to let it reliably execute complex and intelligent investment protection tasks.

Introduction

ASDEX Upgrade is a mid-size Tokamak investigating plasma core and boundary physics relevant for a reactor. Outstanding characteristics are a geometry similar to ITER, a rich set of diagnostics, and high heating power. Today it features about 70 plant systems to diagnose the plasma, operate actuators, continuously monitor the device and feedback control plasma pulses.

Since start of operation in 1992 plant systems have been repeatedly enhanced and many CODAC systems were completely replaced. The initial S5 PLCs, Multi-Transputer plasma control and diagnostics workstations with CAMAC frontends are now largely part of technological history [1][2]. Today, new S7 PLCs, multi-core workstations with high-performance real-time serial IO, industrial control PCs with real-time operating systems, connected through industrial and in-house developed communication networks, are the new standards, with Linux- and LabView-based systems [3] added where reasonable.

However, the major change during the last 16 years has been the way to operate the device and the plant systems. No longer are these regarded as independently operated units, which receive time-controlled triggers to synchronize pre-set activities into a discharge. Instead, the plant systems are integrated through networks and exchange information before and during operation, so that they can be configured as a whole, interacting in real-time to better and more reliably operate and execute plasma discharges and tests.

This paper will give an overview on operation principles and how ASDEX Upgrade´s plant and CODAC systems interac. We will summarize types of plant and CODAC systems and their role (chap.1), explain the experiment operation model (chap.2) and the methods to prepare (chap.3) and execute (chap.4) a pulse, give some notes on framework functionalities (chap.5), and on the protection strategy (chap.6).

1. Plant and CODAC Systems

Plant and CODAC systems operate the various technical installations of a fusion machine to provide the dedicated technical functions needed to run the plant and to prepare and execute pulses. At ASDEX Upgrade most plant systems (≈50) serve diagnostic purposes or evaluate plasma data for control, others serve technical systems (≈20) operating Tokamak actuators (such as power supplies and magnets, heating and fuelling, vessel conditioning, etc.), and some (≈5) perform plasma control (Fig. 1). Depending on their specific task, the plant systems can have a simple or complex internal substructure, ranging from one IO card only in the host bus to multiple subcontrollers with dedicated fieldbusses connecting to a variety of IO cards with thousands of analog and digital IO signals and equipment.

To ease implementation, maintenance, and upgrading, hardware and operating systems are standardized and generic software employed where possible. Diagnostics generally have Solaris workstations as host [4], with real-time serial IO frontend equipment [5] (or with old CAMAC frontend where sufficient). Control is based on industrial PCs running VxWorks (and with dedicated fiber optics IO to diagnostic sensors or technical systems´ actuators where synchronization must be better than provided through real-time networks). Technical systems use SIMATIC S7 PLCs.

All these systems perform their specific task to diagnose plasma or machine, to operate and feedforward control actuators, or feedback control the plasma via these. Furthermore, depending on the task, plant systems locally monitor operation, detect exceptions, and create warnings and alarms, perform self-protection, archive sampled and command data, warnings and alarms, and forward these (partly post-discharge) to the central archive.

The CODAC systems integrate the plant systems for operation and provide the functions to synchronize activities, exchange data among systems before a pulse, assemble and validate a complete and consistent segmented pulse file, and execute it. Dedicated supervisory control exists for the diagnostic plant systems, the plasma control plant systems and the technical systems. These are coordinated through the experiment supervisory control knowing the synchronization and procedures to execute pulses or specific tests with the CODAC and plant systems.

Dedicated networks connect the systems, to exchange asynchronous non-real-time data or data with weak real-time latency requirements (≈milliseconds) over Ethernet, to synchronously exchange real-time data for plasma control with strong latency requirements (≈microseconds) over distributed shared memory, to distribute a phase-locked clock and absolute time information over a in-house developed network, and for hard-wired interlock and safety related communication.

There is no need for an event network, as all real-time taks can exchange arbitrary process data through the synchronous shared memory network, which is fast compared to the millisecond cycle times or operating sytem latencies of the connected plant systems providing evaluated (event) data or driving actuators with such information.

2. Experiment life cycle

ASDEX Upgrade has a broad and vivid scientific program [6]. In view of ITER, various physics and fusion technology related programs are examined concurrently. During each shift 20 to 30 pulses belonging to up to ten programs are executed. To perform such a program, a capability for planning and management of the program and for rapid experimenting in needed, i.e. the ability to flexibly and securely create pulse schedules on base of the actual device condition.

The experiment life cycle starts with a proposal database where scientists can input research ideas by topic any time (Fig.2). In an annual program workshops the physics and technical achievements, planned enhancements and project resources are summarized, and project and ITER relevant topics identified. On that base, proposals are discussed, scientific and technical goals and the annual project schedule adopted, and topics and proposals compiled for discussion with an international scientific program coordination committee. Proposals can subsequently be worked out in detail to define goals and key parameters, and stored into the pulse request database.

Weekly experiment meetings summarize recent physics results, and develop the next week´s work and shift plan on base of the request database, technical and personal resource availability and actual importance. Then pulse file segments and plant system settings are worked out. In most cases the pulse file segments, segment transition conditions, and pertinent plant system settings are re-used form other discharges, possibly modifying a few settings, timing or waveforms.

3. Pulse design

Today, there is a strong trend towards a fully centralized pulse design, where all plant systems are hierarchically operated under control of one complete pulse file defining thousands of settings for plant systems, internal controllers and equipment.

The ASDEX Upgrade apporach is different for organizational and psychological reasons: it combines a decentralized responsibility for plant system officers to configure their systems with specific plant resource characteristics and operation limits compatible with the pulse goals and a central responsibility of the (here: deputy) session leader to provide a plasma pulse file with the right key parameters and scenario segmentation with embedded operation mode transitions and reference waveforms, compatible with the assumed plant systems´ characteristics. I.e. the fine tuning of the plant systems remains in the hand of plant experts and is hidden from the session leaders as user. The pulse file has a high level of abstraction focussing onto physics goals, independent from plant internals, but constrained by operation boundaries and plant characteristics. Organisationally, the parallel editing of plant system settings and pulse file avoids manpower and expertise bottle neck at the session leaders, and gives high satisfaction to plant officers participating directly in experimenting.

The control room is structuerd to support the needed interactions (Fig.3) : session leader and operator face each other, and overlook the diagnosticians pool, while the session leader has the plasma control engineers at hand, the operator connects to plant systems operators in the central control room or in remote control rooms. The resulting short and direct verbal and non-verbal communication paths create a smooth and professional working atmosphere.

During experiment shifts the session leader chooses the prepared (or modified) pulse files, and settings of diagnostics and plant systems, and approves them for execution through the plant operator.

Prior to execution, the diagnostic and technical plant systems are configured with their settings providing the agreed resource characteristics. After these plant systems confirm that their settings are stable, the experiment management process synchronization and parameter server accesses and exchanges all cross-system referenced settings and operation limits in pulse file and plant system, and transforms or validates information, independent of system boundaries in an open parameter space . Another task is to compile the real-time data exchange allocation, based on a publish and subscribe procedure among all real-time plant systems. If all subscribed real-time data are published by exactly one producer, the pulse can be executed, otherwise execution is prohibited because of an inconsistency in the real-time process chain [7].

4. Pulse execution

The experiment management then initiates pulse file download into plasma control [8]. Upon pulse start, plasma control tracks the segment reference waveforms and timing, reads evaluated data and stati from (diagnostic and technical) plant systems, and issues mode transitions and command data to the plant systems to control plant and plasma quantities. At present, plasma control cycles range from 1.5 to 500 milliseconds (dynamically set in the pulse file); vertical stabilization (with passive stabilizing loop) requires around ≈2ms cycles (depending on plasma elongation), heating systems can operate up to ≈2ms, while disruption mitigation benefits from shortest possible latency. Plasma shaping, fuelling, and higher integrated control loops for NTM stabilization etc. operate on timescales of many to many tens of milliseconds [9]. A synchronization scheme has been developed where milliseconds time-synchronized control algorithms can coexist phase-locked with the faster vertical stability control [10].

Scheduling of control processes is data driven, i.e. irrespective of allocation they execute when all required real-time data has become available. The computed real-time data then in turn activate other processes, until the control cycle is complete, and a new one started after the currently set cycle time has elapsed.

A particular feature of ASDEX Upgrade plasma control is the qualification of all real-time data with status tags, central monitoring of proper termination of control processes, and integration with the central interlock. This allows to entrust the plasma control with advanced machine protection tasks, i.e. monitoring of complex interlock conditions and case sensitive intelligent reaction to exceptions, or deviations from the pulse schedule which could not be managed by simple protection systems [12].

5. Framework

Various CODAC services and conventions serve all applications as a framework, such as data archiving and access, error logging and alarm handling, and data naming.

All data follows a name convention to uniquely identify them, with a plant system abbreviation, and hierarchical subnames and numbering, to support pulse definition and its information exchange, allocation and exchange of real-time data, data archiving and data access.

Real-time data exchange between plant systems is automatised using the framework's communication software layer. Communication technology details, data routing and caching are handled by the framework and hidden from the applications, allowing for configurable and relocatable deployment. Processes can read data by taking non-blocking snapshots or operate in data-driven mode, synchronised by availability of new data, while the framework guarantees data consistency. A central publish-subscribe server ensures that each data item requested by a process has exactly one producer and subsequently sets up data transfer between producer and consumers, which may span several networks.

A data quality tagging scheme exists used by publishers of data to inform distributed subscribers about data relevance. This is of particular importance for real-time protection.

Being a pulsed machine, ASDEX Upgrade data can be archived during or after a discharge, while magnets are re-cooled. All data are hierarchically stored into an AFS based archive, together with plant system settings and plant data. Plant data, tagged with absolute time-stamps, are offsett with the absolute time of ignition, to facilitate physics analysis. Data archiving is staged to provide relevant data in shortest time.

6. Protection Strategy

Operating fusion devices bears risks for personnel and machine. These come from radiation, high voltages, high energy densities, thermal and mechanical impact, and high magnetic fields. The protection strategy defines how to minimize risks, and how to prioritize and handle off-normal events to protect health and investment. At ASDEX Upgrade this is done in three tiers:

Health and environmental protection is of highest importance, imposed through laws, engineering standards, and nuclear and non-nuclear operating licensing. A separated safety system handles access control, containment, and radiation monitoring. Implemented as minimal hard-wired logic and PLC, it acts immediately onto plant system actuators, to disconnect high-voltage coil power supplies, suppress heating, and operate automatic doors.

Protection of investment prevents or reduces damage to the device or its components. The interlock system monitors component design limits and self-protects components, or switches the plant off. Implemented locally within the plant systems, and centrally as hard-wired logic and PLC, it is simple and acts immediately onto actuators to perform a coordinated hard-landing sequence for power supplies, magnets and heating systems, or an emergency shut-off to disconnect the machine from the grid.

In the protection hierarchy, CODAC is the first line of defense. It is designed to operate only within the boundaries given by interlock and safety systems, component limits, and plasma stability margins, which are passed to control as operation limits during the pre-pulse configuration.

At ASDEX Upgrade CODAC, control and interlock are not separated but complementary, as it is not obvious how a simplified separate interlock could more precisely monitor complex limits and terminate a high-performance discharge in a smoother way than control could do. As ASDEX Upgrade´s control has built-in features to run critical applications it can be charged with complex protection tasks [13]. The actual implementation includes real-time handling and correction of invalid input signals and degraded or saturated plant system actuators, detection of simple and complex component failures and physics stability margins, clipping of feedforward and feedback commands to operation limits. Furthermore, it can switch-over to alternate pulse segments according to specific programmable transition rules, or compute new reference values in real-time to stabilize a pulse. Finally it can trigger the interlock system when operation limits are exceeded, indicating a loss of control situation.
This is to say that our general strategy is to continuously enhance off-normal event-handling in the real-time control to continue discharges or perform soft-landing, backed by a robust hard-landing procedure synchronized by the interlock system.

By priority of their actions, control, interlock, and safety appear to form a protection hierarchy. This is true for control and interlock, which share the goal of investment protection at different trigger levels. Safety, however, generally has no higher trigger levels, but aims at an orthogonal protection goal.

Summary

An overview of ASDEX Upgrade´s CODAC system has been given. Plant systems have been continuously enhanced and modernized, and today reside on workstations with fast serial data IO, industrial PCs and PLCs for diagnostics, control and technical systems. These are connected through a standard set of dedicated communication networks.

Plant systems, that were initially operated separately, have been integrated under the central CODAC system.

The physics program is developed in an experiment cycle and supported with tools and continuously refined descriptions for research proposals, pulse requests and pulse schedules. These are compiled in a distributed task among plant engineers and session leader, linked through a description about the required plant characteristics, and cross referenced and validated prior to pulse execution.

Pulses are run on a distributed network of real-time controllers, diagnostics and technical plant systems, which also handle complex and intelligent off-normal events as part of a general protection strategy integrating operation and interlock, with separate safety tasks.

References

[1] G. Raupp, H. Bruhns, K. Förster, F. Hertweck, R. Huber, A. Juelich, G. Neu, H. Richter, U. Schneider, B. Streibl, W. Woyke, D. Zasche, T. Zehetbauer, ASDEX Upgrade Team,
ASDEX Upgrade Discharge Control and Shot Management, Fusion Technology (1992), p. 1072

[2] K. Behler, H. Blank, A. Buhler, R. Drube, H. Friedrich, K. Förster, K. Hallatschek, P. Heimann, F. Hertweck, J. Maier, R. Merkel, M.G. Paco-Düchs, G. Raupp, H. Reuter, U. Schneider-Maxon, R. Tisma, M. Zilker, Computer Science Division, Garching Computer Centre, ASDEX Upgrade Team, Review of the ASDEX Upgrade data acquisition environment – present operation and future requirements, FED 43 (1999), pp. 247-258

[3] L. Giannone, W. Schneider, P. J. McCarthy, A. C. C. Sips, W. Treutterer, K. Behler, T. Eich, J. C. Fuchs, N. Hicks, A. Kallenbach, M. Maraschek, A. Mlynek, G. Neu, G. Pautasso, G. Raupp, M. Reich, K. H. Schuhbeck, J. Stober, F. Volpe, T. Zehetbauer and ASDEX Upgrade Team, Real time magnetic probe and flux loop measurements for tokamak control with a multi-core PCIe system, this conference

[4] K. Behler, H. Blank, H. Eixenberger, H. Lohs, K. Lüddecke, R. Merkel, G. Raupp, G. Schramm, W. Treutterer, M. Zilker, ASDEX Upgrade Team, Real-time Diagnostics at ASDEX Upgrade - Architecture and Operation, FED 83(2-3) (2008), pp. 304-311

[5] A. Lohs, K. Behler, K. Lüddecke, G. Raupp, and ASDEX Upgrade Team, The ASDEX Upgrade UTDC and DIO cards – a family of PCI/cPCI devices for real-time DAQ under Solaris, FED 81 (2006) p.1859-1862

[6] V. Mertens, G. Raupp, W. Treutterer: Plasma Control in ASDEX Upgrade, Fusion Science and Technology, 44 (3) p.593

[7] G. Raupp,, G. Neu, W. Treutterer, V. Mertens, D. Zasche and Th. Zehetbauer, and ASDEX Upgrade Team, Control process structure of ASDEX Upgrade's new Control and Data Acquisition System, FED 74 (2005) 697-705

[8] W. Treutterer, G. Neu, G. Raupp, D. Zasche, Th. Zehetbauer, and ASDEX Upgrade Team, ASDEX Upgrade's new Plama Control Scheme, 2005, FED 81 (2006) p.1927-1932

[9] A. Manini, J. Berrino, S. Cirant, G. D'Antona, F. Gandini, G. Grünwald, F. Leuterer, M. Maraschek, F. Monaco, G. Neu, G. Raupp, D. Sormani, J. Stober, W. Suttrop, W. Treutterer, D. Wagner, H. Zohm, ASDEX Upgrade Team, Development of a Feedback System to Control MHD Instabilities in ASDEX Upgrade, FED 82 (2007), pp. 995-1001

[10] W. Treutterer, K. Behler, L. Giannone, N. Hicks, A. Manini, M. Maraschek, G. Raupp, M. Reich, A. C. C. Sips, J. Stober, W. Suttrop, ASDEX Upgrade Team, Real-time Diagnostics at ASDEX Upgrade - Integration with MHD Feedback Control, FED 83(2-3) (2008), pp. 300-303

[11] W. Treutterer, K. Behler, L. Giannone, K. Lueddecke(2), G. Neu, G. Raupp, D. Zasche, T. Zehetbauer, and ASDEX Upgrade Team, Real-Time Diagnostic Integration with the ASDEX Upgrade Control System, this conference

[12] W. Treutterer, K. Behler, A. Lohs, G. Neu, G. Raupp, D. Zasche, Th. Zehetbauer, R. Cole, K. Lüddecke, Software structure and real-time signal exchange for the ASDEX Upgrade tokamak control system, in: Proceedings of the International Conference on Accelerator and Large Experimental Physics Control Systems, Gyeon-Gju, South Korea, 2003, pp 548-550

[13] G. Raupp, W. Treutterer, V. Mertens, G.Neu, A. Sips, D. Zasche, T. Zehetbauer, and the ASDEX Upgrade Team; Control processes and machine protection on ASDEX Upgrade, FED 82 (2007) p.1102-1110

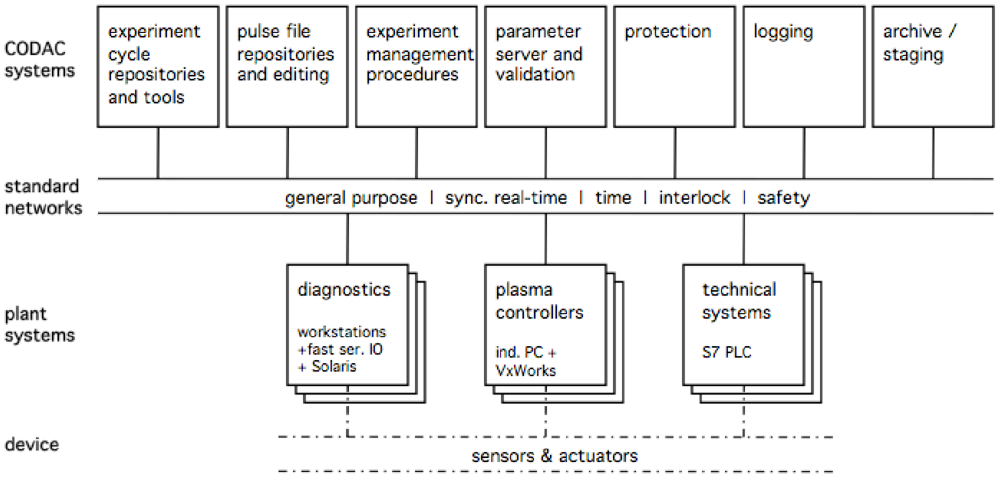

Fig.1 : CODAC and plant sytsem overview

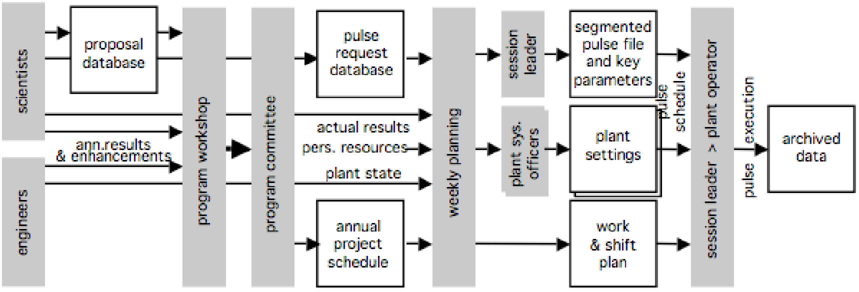

Fig. 2 : Experiment life cycle

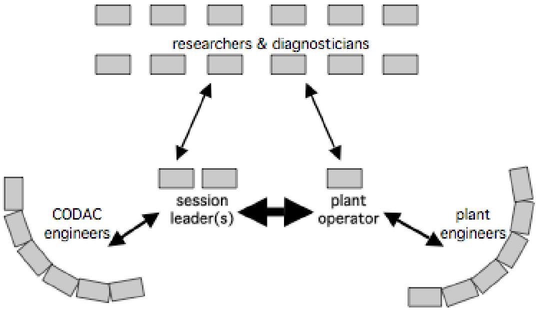

Fig. 3 : Control room layout and communication paths

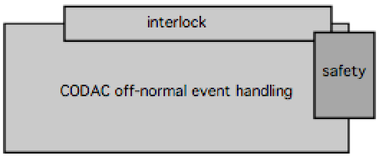

Fig. 4 : Schema of the protection instances and hierarchy