Integrated Software Development for Wendelstein 7-X

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Abstract: Steady-state fusion devices, such as Wendelstein 7-X, pose a new challenge to the software capabilities for control, data acquisition and data analysis. These software modules must cope with huge amounts of streaming data. Proof-of-principle demonstrations of important steps in a physically motivated framework are shown to be feasible. This includes integrated data analysis from different diagnostics and coupling of modeling codes, even for advanced device control. The present approach makes use of a strict modular design and already allows the use of modules in present design and optimization studies of device components and diagnostics setups. A striking benefit is provided by embedding validated legacy codes within a service oriented software architecture, thereby ameliorating incompatibility issues. The implementation of such a demanding framework makes the incorporation of modern information technologies necessary.

1. Introduction

The W7-X mission comprises the exploration of the reactor capabilities including the steady state operation. This makes the W7X Software Project a large development project with the task of integrating the necessary software components in a “view & react” rather than a “shoot & collect” paradigm. The physics goals of Wendelstein 7-X demand software tools for interpretive and predictive investigations of the 3D magnetic confinement. Under operation, these tools must exhibit analysis capabilities immediately supporting a physics-driven experimental program and device control. Since W7-X explores reactor capabilities of optimized stellarators, all software components must be prepared for steady-state operation. This is more demanding than long-pulse operation and it poses new challenges with respect to continuous operation, device control, data acquisition, analysis of diagnostic data and the inclusion of physical modeling.

Central requirements for the next-generation steady-state fusion devices are automated analysis procedures due to the huge amounts of data and real-time processes which must be dealt with in order to make full use of the steady-state operation. Rapid on-line analysis is not only a requirement for monitoring physics quantities (which allow human interaction) but it also allows physics-based control schemes and safety-relevant supervision, e.g., the on-line detection of overloaded first wall and divertor target elements.

2. Physical modeling

The physics basis for preparatory work is systematic predictive modeling. As a basis for design, predictive power and density scans typical W7-X configurations are employed for physical reference scenarios. These scenarios will guide the development process of the experiment setup, in particular the plasma diagnostic development, and the development of physics driven plasma control. Stellarator plasmas are considered to be stable, i.e. no plasma position stabilization like in tokamaks is necessary to sustain the plasma. Even in discharges with enforced disruptive events, like the current driven tearing modes, the plasma recovers immediately again [1]. However, the steady state operation forces to implement a new type of stellarator device control in order to drive the plasma into the desired state. The time constants being involved are typically long, causing the need to predict the evolution of the plasma with respect to the plasma parameter of interest. Hence, feedback loops alone are not suited to control the plasma due to feedback oscillations caused by the long plasma reaction times. The shortest time constant under consideration is in the order of about 100 ms for the energy confinement time τ_e, and the longest one is expected to be in the order of several minutes for the thermal equilibrium of the wall τ_{wall}.

Based on the experience gained from existing stellarators [2], an important issue for the steady state divertor operation in low shear stellarators like W7-X is the control of the edge magnetic configuration. The distance between the X-points and target plates is crucial for achieving the favorable detached edge plasmas, in which most of the power flux is radiated and the local heat load onto the divertor target is reduced. Although the bootstrap current in most of the W7-X configurations is strongly reduced ($I_p < 50$ kA) a small current fraction is sufficient to significantly change the configuration (Figure 1).

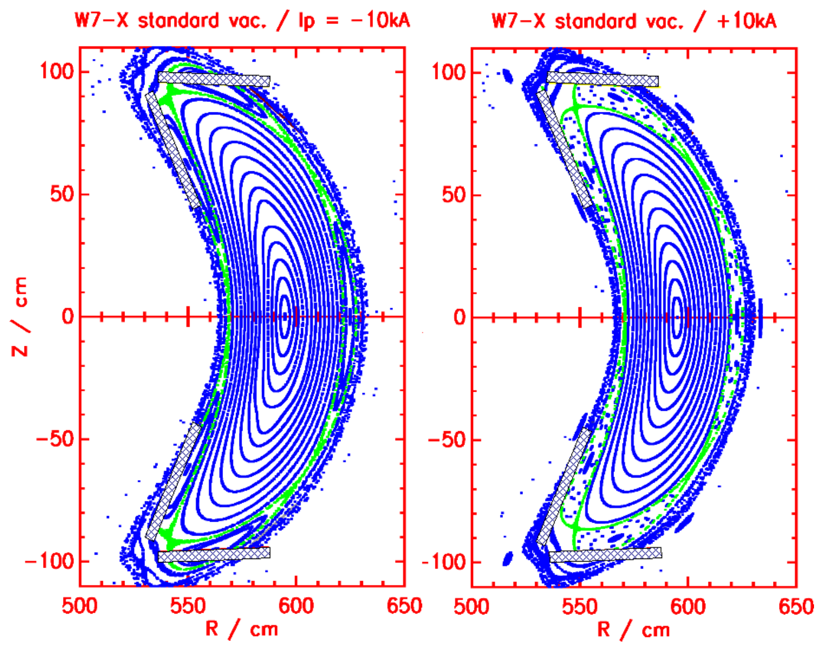

FIG. 1: W7-X standard magnetic configuration for different bootstrap current values (+/-10 kA). The green point indicate the separatrix. The X point distance to the target plates (shaded area) varies like 2.5mm / kA.

Recently, the evolution of the current density profile and the skin and L/R time constants have been investigated [3]. The bootstrap current is calculated from neoclassical theory and evolves for typical plasma parameters on the L/R-time scale of about 20 s. The target thermal equilibrium times are in the order of 3 s and do not allow to react properly in case of an edge magnetic configuration change. It is intended to compensate this residual bootstrap current by virtue of ECRH current drive. The requested ECCD can be obtained either by the movable mirror system or by power control of the current-driving gyrotrons. In this case it is expected that predictive modeling is essential for a successful steady state edge configuration stabilization, since only feed-forward plasma control overcomes the problem of the long time constants being involved.

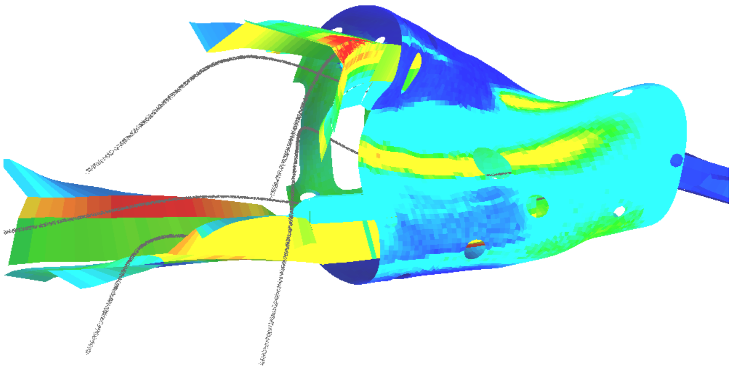

FIG. 2: Heat loads on the W7-X plasma vessel and divertor structure by plasma radiation emitted from the X-Points (scattered gray line). The color indicates the heat-flux, red 130 kWm^{-2} down to blue 0 kWm^{-2} .

Further control issues are defined by the need to drive the plasma into certain high performance states, like the optimum confinement modes, characterized by narrow density profiles and particle transport and heat conduction on a neoclassical level in the plasma core. High performance discharges with rather broad density profiles like the quiescent H-mode and the HDH-mode [4] should be also investigated in steady state discharges. In particular the high edge density in HDH discharges might be essential for proper divertor operation in W7-X. The need for active density profile control by central fueling has been stated already in [5] in order to avoid hollow density profiles in large optimized stellarators. The impurity accumulation in the quiescent H-mode and also in the neoclassical optimum confinement discharges may be reduced to a less critical level if enhanced anomalous impurity transport at the edge can be established, e.g. by ELM-like MHD activity. It is not yet clear how to establish in a controlled way the edge MHD activity, but it might be worth to have tools for tailoring the edge temperature and density profiles.

The control of profiles, the prediction of the bootstrap current and the ECCD, the prediction of power deposition and the on-line data analysis needs an essential modeling tool, the on-line equilibrium determination. The calculation of 3D MHD equilibria requires typically a large computational effort, making on-line equilibrium provision on a 100 ms time scale impossible. Different codes for calculation of the 3D MHD equilbria, like VMEC [6], PIES [7] and HINT [8] are in use for the off-line calculation. Such results can be used in order to develop the function parametrization or neural networks for fast equilibrium determination [9][10].

The physics modeling software modules play also a relevant role for the safe machine operation. Thermal equilibrium time constants of the first wall elements range from a few seconds to a few minutes. On the basis of these time intervals the plasma controller has to decide how to counteract to a possible thermal overload. Helpful in this respect is the prediction of the heat load, not only for the directly wet surfaces but also for more hidden components such as the cryo pumps behind the divertor. In FIG. 2 the heat flux through divertor pump slits has been calculated under the assumption of X-point radiation, which is non-trivial due to the 3D divertor geometry. Such software modules as shown in the present example combine the different physics software modules and both physical and engineering data sources. In the most cases, these software modules are needed for the diagnostics design as well. It is the major objective of the integrated software development to use the same software modules for the different purposes right from the start.

3. Data analysis

Manual data analysis in expensive steady state experiments should be reduced to a minimum in order to reach a maximum amount of analyzed discharges over the almost full discharge duration. This can be achieved only if the data analysis becomes as convenient as possible and is automated wherever possible. A precondition for convenience in data analysis and also in physics modeling is to offer well defined software modules with well documented interfaces and well structured databases for computationally expensive results. Furthermore, automated data analysis enables a systematic combination of different diagnostics by virtue of the *integrated data analysis,* which is based on standardized procedures, e.g. with respect to uncertainties. The analysis of diagnostic data based on Bayesian statistical models has been carried out successfully for the Thomson scattering system in W7-AS [11]. The inclusion of all uncertainties of quantities needed for data analysis leads to the so called posterior probability distribution function in electron density and temperature. Such results can be significantly improved and made more reliable by applying this method to integrated Bayesian diagnostic models. This has been demonstrated for the W7-AS diagnostics, where a higher certainty of plasma parameters (n_e, T_e) is achieved by systematic inclusion of different diagnostics [12]. In this case, the probability distribution of the Thomson scattering results under inclusion of soft X-ray temperature and microwave cut-off density information has become much more narrow. The optimum solution to the integrated data analysis problem is to combine as much information on the plasma as possible. In [13], a major step is the inclusion of the magnetic flux surface mapping, because diagnostic data itself typically depends on it and, on the other hand, the magnetic equilibrium (mapping) depends on diagnostic data (pressure profile). This flux surface mapping uncertainty due to uncertain pressure profile and parallel current density profiles requires an integrated plasma model, including the MHD equilibrium, preventing artificial iteration processes of analysis module chains. The same approach can be used for the preparation of diagnostics, based on the inclusion of same or similar diagnostics models and is currently under investigation for combined diagnostic design optimization of Thomson scattering and interferometry [14].

The integrated data analysis is intended to be used for off-line data evaluation due to the computational effort that is needed. However, the integrated analysis software modules are needed for the validation of fast analysis modules, either based on analytical approximations, function parametrization or artificial neural networks. An important example in this respect is the function parametrization of 3D MHD equilibria, which is so far the only opportunity to get real time flux surface mapping in a stellarator. This approach even allows to describe complex dependencies such as magnetic island width and separatrix positions [10].

On the other hand the integrated data analysis takes advantage of proper detection of interesting or unexpected measurements to focus the attention on important events.

Committees of Bayesian neural networks [15][16] applied to the evaluation of multi-channel Soft-X-ray diagnostics combine two appealing properties: The networks are fast enough to allow a continuous monitoring of the 2-D emission profile and at the same time signaling measurements outside of the expected scope. Bayesian neural networks are a promising alternative in areas where the continuous operation mode excludes the direct solution of nonlinear models. Such fast modules are intended to be used in the W7-X data acquisition system for on-line analysis [17] and for plasma control purposes in the device control system [18]. The on-line modules should become real-time capable (guaranteed response times), where necessary, and are prepared to be "pluggable" into the W7-X data acquisition and machine control system.

4. Data acquisition and device control

A precondition for the implementation of an integrated analysis and modeling software framework is the coupling of code modules and the establishment of a well-structured "data base" for all quantities of interest. The W7-X data acquisition system is based on an object database for the storage of raw data and derived results. Inside this database, objects for the description of the experiment configuration exist, which contain also required information needed for a proper data analysis [19]. It is essential for the on-line analysis and also for the active plasma control to plug the physics analysis and modeling modules to the data acquisition system. The data analysis modules need information about the data sources to be used, dependencies on other analysis modules and the related time groups containing data, time stamps and control parameter. The interface of the analysis modules is therefore defined by the specifications given in [20].

Different scenarios for the discharge operation exist. These are short pulses of a few second durations, long pulses with objectives and device configurations changing in time and steady state discharges, in which a certain plasma state is being kept for infinite time (approx. ½ h in W7-X). In order to fulfill the requirements given by these three different discharge types a segment based control concept has been chosen for W7-X [21][22], in which each segment has its own configuration. In particular the active plasma control can be included segment wise giving a maximum flexibility in plasma operation. Active plasma control on a time basis of the energy confinement time (100 ms) is implemented in the data acquisition system. These computers do not have hard real time requirements and provide a typical modern software environment. In cases of real time control applications down to a time basis of 1 ms, the software analysis and control modules have to be implemented in component segment control systems as described in [23], e.g. the component control system for the gas valves receives information of the line density and digital real time controller software calculates the required valve voltage.

These different systems need to use common data sources and analysis modules wherever possible. At present, the W7-X software project takes care for the unification of the data sources and interfaces, since one major objective is to have all information appearing virtually as a single database. This objective has its origin in the automated analysis, which can only work properly if all necessary information can be accessed inside the computer codes. Besides the storage of raw signal data and machine control parameters, the following databases are currently in development or envisaged:

- Physical scenario database

- Confinement database
- Profile database
- Transport coefficient database
- Magnetic configuration database [24], extension to 3D magnetic field database for edge physics
- Component database (geometry, material properties)
- System integration data (e.g. cabling, pipes)
- Relevant atomic and nuclear data
- Log-book
- Administrative data

5. Software development, framework and infrastructure

The applications of the W7-X software described above have a strong impact on the choice of the software development tools. Furthermore, the long lifetime of the project of roughly three decades implies not to rely on a single information technology or programming language. Therefore, the W7-X software project supports a heterogeneous framework, i.e. multi-platform and multi-language environment, rather than a homogeneous one. This will allow the smooth transition to new information technologies if worthwhile.
The framework is intended to be based on service oriented architectures [25]. This

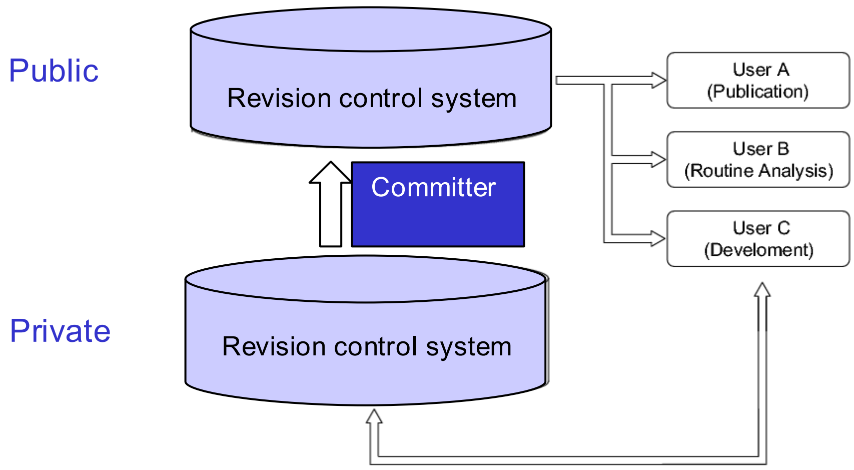

FIG. 3: Public/private scheme of the software repositories.

framework, in which many individual codes created by scientists are deployed via services, is very different to the widely used GRID architecture, in which many computer nodes across the world form a large multi-processor environment. Currently, WebServices, which was the underlying technology used in [13], are under evaluation. A striking feature of the service oriented architecture is the possibility of legacy code integration, since validated codes, e.g. MHD equilibrium solver, should be integrated in the present form and recoding has to be avoided.
For the software development it is essential to use common source code repositories. This has been implemented by using a system which also handles the history of code development (SubVersion [26]). It is planned to have two of such repositories (FIG. 3), a *private* one for the individual developers and a *public* one containing the official releases. In order to avoid too

many software branches, the developers have to take the code basis out of the public repository for the continuation of the code development. Release candidates have to be tested by the commission process before becoming an official software release. This procedure is essential for a homogeneous and coordinated software development and is based on the ideas of the open source community.
A key issue in the development process is the documentation of all the steps that are necessary for the software creation. These steps comprise the definition of the particular requirements, the analysis, the software design and its implementation. Later on, such software pieces have to be integrated into a large framework, which allows finally validate and verify these codes. The W7-X software project employs the unified modeling language (UML2) for the analysis and design of the software packages. At present, the commercial software package MagicDraw® is in use, which can be used for several object oriented programming languages (mainly Java and C++). Class and sequence diagrams are used for the early detection of conceptual failures. Additionally, this way of development allows to use well defined software pattern [27], to ease the communication with other developers or, in case of a new pattern, to reuse them in other sub-projects as well. The detailed documentation of classes and functions, the documentation of the application programming interface (API), has been already automated by a tool named DocSys, that has been developed at IPP. This tool daily creates the documentation out of the source codes that are in the repository by using documentation generators like doxygen, javadoc, f90doc and rdoc. These tools take comments in the source code of specific form and derive HTML pages, which can be simply accessed by standard Web browsers.

6. Outlook

Software developments for W7-X employ state-of-the-art information technologies to meet with physics requirements and resulting steady state issues. The service oriented concept allows the integration of different software components ranging from modeling and data analysis to data acquisition and control. Shared infrastructure and data repositories are not only used for an increased efficiency but are the basis for physics driven experiment operation in steady state. Proof of principle components exist and parts of the infrastructure are set up. One of the next step is the application on the WEGA stellarator as a W7-X test bed.

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