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Real-time current profile measurements for NTM control

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Advanced scenarios [1] are thought to be a key ingredient to achieving efficient fusion power. These scenarios differ from standard scenarios primarily by the shape of the current density profile. The occurrence of magneto-hydrodynamic modes (due to pressure gradients, fast particle excitation, etc.) is also closely related to the exact shape of the q-profile. Modes, which usually deteriorate the plasma confinement, can affect the q-profile and vice versa. An avoidance of MHD modes or a controlled triggering of benign modes in order to avoid more deleterious ones is therefore desired.

The method of choice for controlling and avoiding neoclassical tearing modes (NTM) at ASDEX Upgrade is the deposition of ECCD inside the magnetic island for stabilization [2] by moving a mirror, which directs the ECRH beam at the proper position in the plasma. In order to successfully achieve this in real-time it is necessary to know the approximate position of the mode already in advance of the actual start of the mode. Also, when the mode is locked to a vessel component and not rotating with the plasma, location determination by other means is impossible, so that it is mandatory to know the position of the rational surfaces, on which the NTMs are located. In order to do so, an accurate flux surface geometry and the proper current profile also in the core needs to be available within very short time (at least << growth time of the mode ~ 100 ms). Moreover, when countermeasures are applied early enough, less power is necessary to avoid the mode completely [3]. Our method to achieve this fast enough is function parametrization of magnetic signals [4], which has already been shown to provide the necessary results within less than 2 ms using purely magnetic data [5]. However, without measurements near the plasma center, the core current profile, which is the key quantity to locate rational surfaces, is only vaguely known or even determined incorrectly. By including (real-time) MSE measurements, the situation can be improved and rational surfaces accurately located.

The MSE-diagnostic relies on the splitting of the high energy (60keV) neutral beam Balmer line as a result of the strong motional electric field (E = v x B) produced in the rest frame of the neutral deuterium atoms. Deuterium exhibits a linear and thus very strong Stark effect, which dominates the line spectrum when compared to the Zeeman-effect. Since the spectral components are linearly polarized parallel or perpendicular to the electric field, a measurement of the field line pitch and together with the magnetic information also the current density profile, becomes possible.

Since the inclusion of MSE data in the function parametrization code requires the integration of data from different diagnostics in real-time, a task expected to be more and more important in the experimental development, a more general framework allowing real-time standard diagnostics was developed [6]. The hardware uses a universal transfer protocol (SIO, serial input output) to transport data, which is captured by individually configured data acquisition modules (standard ADCs, phase counters, pulse counters, 2D spectroscopic data, etc.), across fiber optical links to receiver boards connected to the PCI bus of standard computer hardware. Before the data transfer occurs, though, the built-in FPGA logic multiplexes each set of data samples with a time stamp (nanoseconds as 64 bit unsigned long long) representing the absolute time of data acquisition which is kept in sync with all (RT-)diagnostics of the whole experiment due to a TDC (time to digital conversion) module linked to the central timer across a fiber optical connection. The operating system on the DAQ computers has to support DMA access, but is otherwise not limited to a particular type. The first implementation uses the SPARC hardware platform running Sun Solaris 10 as the operating system. An implementation for vxWorks exist, an x86-Solaris and possibly x86-Linux are planned. The current production systems are delivering data with up to 64 MSamples/s to a single computer across the PCI bus. After typically 10 seconds of data acquisition, the whole memory is read by a DAQ thread and data is written to a standardized file format, where it can be retrieved later by standard library calls.

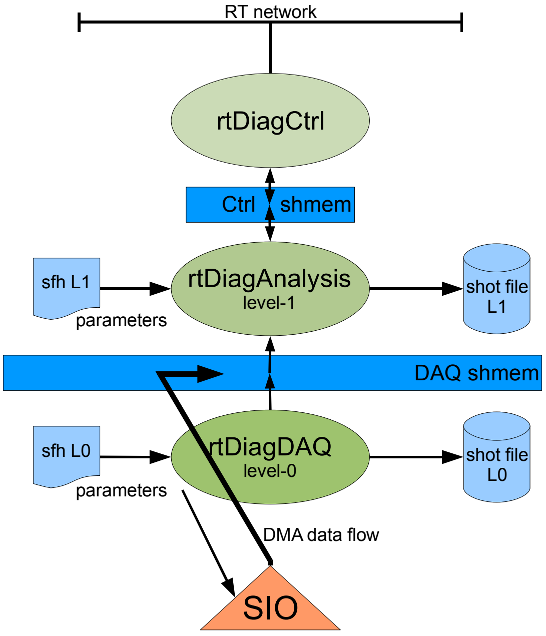

Figure 1: Overview of AUG real-time diagnostic

Even while the raw data, which is streaming across the SIO link, is transferred to memory by means of direct memory access (low CPU demand), a second thread can access them as they are generated. Due to the intelligent way of wrapping this memory access in backwards-compatible routines, it is possible to transparently develop algorithms, test them on old data and – once they meet the required specifications – run the identical code on newly generated data with but a minor change in the configuration file of the analysis software.

A special protocol handles the transmission of result data across several optional paths (reflective memory, UDP ethernet network, carrier pigeons) to the central control of the experiment [7], where it is either routed to different recipients or used directly to affect the plasma by adequate actuators, i.e. ECCD (electron cyclotron current drive).

For the MSE algorithm, some performance figures have already been collected. The raw signals produced by photomultiplier tubes behind a setup utilizing the PEM modulation technique are digitized by ADC modules hooked up with a SIO based DAQ system and can be accessed in computer memory while the DAQ is still going on. The necessary library calls (which are still subject to further profiling optimizations) impose some overhead on each subroutine call. For the MSE, which currently collects 16 signals sampled at 250 kHz, the overhead amounts to about 30% of the data acquisition time. That means, for 2 ms of data in memory, about 1400 us remain for calculation of useful control parameters or FPP input data, respectively, and their transmission to the recipients. The first implemented algorithm is fast enough on the dedicated SPARC computer, to allow continuous DAQ (level 0), result production (level 1) and transmission of data across an appropriate network. Preliminary tests on x86 hardware (offline, using old data) suggest that performance may increase by more than a factor of 2 if the code is mostly based on floating point arithmetic. Appropriate compilers may net another gain of about 25 %, so that a figure of 600 us cycle time per 2 ms of raw data is feasible, once x86-based computers, which can also run the SIO cards, are available. In case of the MSE real-time algorithm, this means that additional filtering, more sophisticated evaluation or faster data rates can be achieved.

In order to assess the operational window of the ECCD enabled current profile control, a preparatory plasma experiment was performed using an earlier prototype system. The discharge with a current of 800 kA and a toroidal field of 2.1 T was run with 2 sources of NBI thus generated a stable H-mode. In order to shape the current profile, one of the beams with a relatively broad power deposition profile, heating ions and electrons alike, was replaced by pure electron heating in the ECCD mode of operation. The total input power of about 1.6 MW was matched by reducing the extraction voltage of the neutral beam. As can be seen from the time traces (figure 2) of the MSE angles, there is a clear, reversible response of the magnetic pitch angle measurements to the substitution of NBI heating by ECRH. This is attributed in small part to changes in the current profile and to some degree to changes in the fast particle pressure profile. While small changes in electron temperature are visible, ion temperatures and stored energy are constant within a few percent across the switch-over between the different heating methods. The absolute change of magnetic field angle as seen by the MSE diagnostic, which

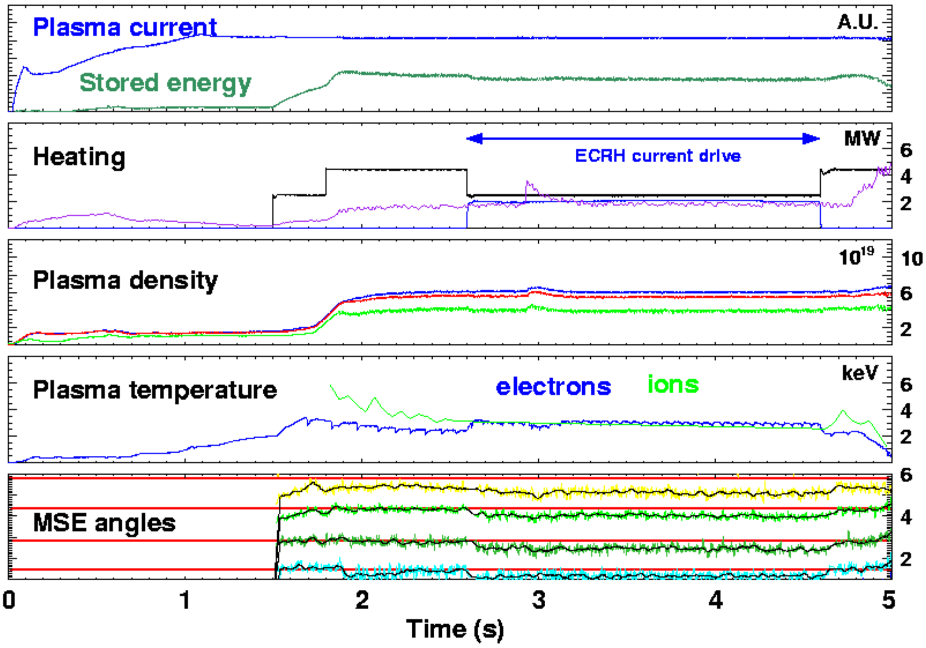

Figure 2: Reference discharge for test of actuator ECCD

could be used as a low-order control parameter, however, is changing only marginally outside the noise band and thus not yet sufficient to act upon in a dedicated control loop. Algorithms to switch the NBI and ECRH during the run-time of a discharge on certain trigger conditions have already been implemented and used in other experiments. Once more sophisticated algorithms to remove some of the noise are available or a stronger actuator for shaping the current profile (e.g. higher ECCD power) are available, we will be able to demonstrate the capabilities of the integrated real-time loop in a straightforward experiment.

Current activity is focusing on providing the FP algorithm with MSE measurements in real-time with low enough latency in order to achieve the desired and validated results for the location of rational surfaces in the current profile. Once this is achieved this enables the next stage of the NTM control project. We expect to have a fully integrated control loop by the end of the year.

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