# Management of Real Time Processes for Plasma Parameter Optimization at ASDEX Upgrade

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*Abstract*

Beyond optimization of position and shape control, producing high performance plasmas relies on precise and coordinated control of plasma parameters. This requires a universal platform, into which control algorithms can flexibly be integrated to adapt to interesting discharge scenarios. With the multitude of processes expected to be implemented, management of real time processes becomes crucial. In this paper we shall demonstrate how this issue is raised by the requirement specification of the controller and how it influences its design, implementation and operation.

## I INTRODUCTION

Active real time control is a prerequisite in making the tokamak a serious candidate for a future fusion reactor.

First and foremost, plasma equilibria have to be obtained: reactor relevant tokamak plasmas are elongated and thus inherently unstable, requiring fast position feedback control. Divertor configurations demand precise control of the outer shape. Albeit complex, position and shape control can today be considered a technical task, because the underlying physics is well understood. Based on theoretical models for plasma equilibrium, numerous devices and algorithms have been implemented [1, 2, 3].

However, progress in fusion physics depends on the ability to control divertor characteristics and bulk plasma parameters. Since the physics of confinement is not yet fully understood, improvements must be achieved by a symbiosis between plasma physics and controller development. This is to say that physical knowledge gained from experiments or theoretical considerations will flow into new or better control methods. These in turn result in improved plasmas under well-controlled conditions, thus leading to a better understanding of confinement.

A controller platform participating in such a knowledge cycle gains a new quality in that it becomes an immediate tool for the physicist, and as such part of the physical research process itself [Fig. 1].

At ASDEX Upgrade we showed that such a multi-purpose plasma parameter controller can actually be designed, built and successfully operated [4]. It is able to perform a number of independent single variable control algorithms, which has also been done by other experiments [5, 6, 7]. Application of this facility has already helped to discover a new confinement regime: the completely detached H mode [8].

However, to make full use of the controller's potential for concurrent real time control, and to reflect the coupling of controlled parameters in the plasma, single value control processes must be given a means to interact with each other. This adds to the complexity of both the technical implementation and the user interface. As a consequence, we decided to introduce a new conceptual layer for management of real time processes.

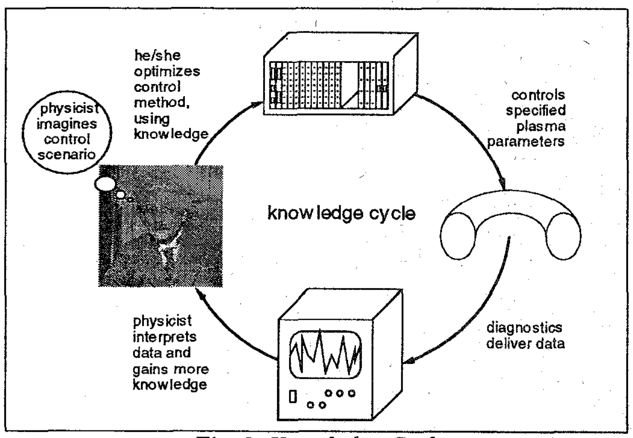


*Fig. 1: Knowledge Cycle.*

In the next chapters we shall outline the requirement specification, and show how real time process management influences design and implementation of the controller and how it greatly simplifies its parametrization.

## II REQUIREMENTS FOR PLASMA PARAMETER OPTIMIZATION

The general framework mentioned above forces a number of constraints and requirements on system structure and operational behaviour of the generic controller to be designed.

Equilibrium control and plasma parameter control differ according to the time scales of the underlying physical

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processes: whereas the former are governed by the resistive time scale, the latter occur on the slower diffusive one. Moreover, control of equilibrium and of plasma parameters require different approaches: precise theoretical models of position and shape control allows for a self-contained system specification, whereas plasma parameter control based on empirical knowledge requires an open platform. We concluded that the two control tasks are best performed by separate devices.

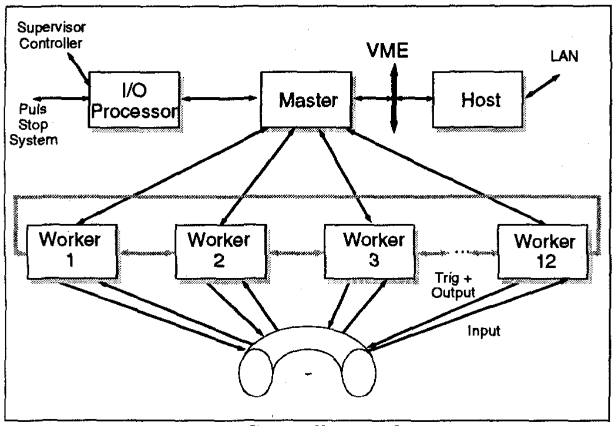


*Fig. 2: Controller hardware.*

The dedicated plasma parameter controller needs access to all refuelling and heating actuators. Actual values for feedback control are not directly available, but must be derived from a large number of diagnostic signals. The various sensor-actuator combinations will correspond to a large number of optional control processes. These may initially be few and simple, but continuously expanding in number and size, due to the heuristic approach. The controller should be scalable in that its growth should not result in degradation of I/O and computing performance and manageability.

Assuming that there is sufficient computing power to execute the control algorithms at appropriate speed, flexibility becomes the most important design criterion.

Structures for I/O, interprocess communication and process control should provide a backbone with clean interfaces for easy addition, replacement or modification of control processes. As concurrent single control processes will generally have to run on individual cycle times, eventual information exchange between them must be handled asynchronously. Generally speaking, communication and control layers must hide architectural constraints from the logical process structure.

Further constraints arise within the logical process structure itself: of all possible combinations of elementary processes only those satisfying certain technical and physical conditions are actually useful. Technically a combination must be complete (no member process requiring communication with non-members), free of communication deadlocks, and collisions (no two processes simultaneously accessing any actuator). From the physical point of view only those amongst these are of interest which represent a valid physical control scenario. Therefore process management mechanisms must be provided which ensure that only meaningful combinations are selectable and that transitions between them are performed coherently at given times or plasma states.

Coordinated action with the existing real-time control system must be guaranteed: integration into the supervision control, ability to execute the common discharge program and to contribute to the common discharge protocol, and embedding in the protection system [9].

## III CONTROLLER HARDWARE AND COMMUNICATION MODEL

The plasma parameter controller built for ASDEX Upgrade has the required features: scalability was achieved by a multi-processor design based on transputers. A set of twelve worker transputers provides sufficient I/O and computing power [Fig. 2].

Two links of each worker reach out to its neighbours, forming an interprocessor communication ring, and the two remaining links are used for local peripheral I/O, multiplexed to input about 100 diagnostic signals and to control all (≈20) heating and refuelling actuators of the experiment. A common master transputer synchronizes the workers for discharge operation, and coordinates actions with the discharge control supervisor via a separate communication processor. The advantage is that due to the static I/O connection to periphery and the private input trigger system on each worker, control processes on different workers can run with different cycle times.

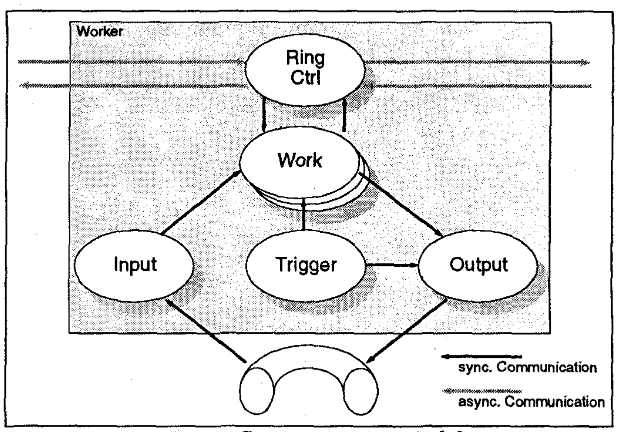


*Fig. 3: Communication Model.*

If information were directly exchanged across processor boundaries, however, all participating processes would have to wait for each other, causing cycle times to be synchronized to the slowest one. To avoid this, processors need to be decoupled by software for buffered asynchronous interprocess communication. With control cycles and communication times much shorter than response times of actuators or the time scales of the physical processes involved, it does not matter if data in buffers are from the previous input cycle. Nevertheless, when mapping processes to processors, besides load allotment and cycle time constraints, the minimisation of ring communication distances is an optimization parameter to be considered.

The communication model thus consists of identically structured processors performing local I/O, and of a global software ring communication bus to distribute information among them [Fig. 3].

The ring communication bus is implemented as one ring communication module (rcm) per processor. Rcms run on high priority and independently from the local software cycle. Each rcm has buffered interfaces to the rcms on its two neighbouring processors and to all local work modules that wish to exchange data on the ring. The data protocol consists of a unique identifier, a value, and status information. Each rcm manages a table containing an entry for each data item. The entry corresponds to the data protocol plus local routing information. The latter is used to determine if incoming data should be sent to one or both neighbours on the ring. Therefore, apart from the identifier, the work modules need not maintain any information about data they want to exchange. This results in a clear and easy-to-use interface for the insertion of new work modules or their re-allocation to a different processor.

From the communication model one can see that the controller is well-suited for the implementation of concurrent but weakly coupled control processes that do not suffer from communication delays on the order of one cycle time. Independent, i.e. non-communicating processes can also be implemented, of course. Should the need arise to have more than one worker assigned to the same control task, it is possible to implement strongly coupled processes - with synchronized cycles - on clusters of workers on the ring, without severely compromising the performance of the global communication layer.

## IV REAL TIME PROCESS MANAGEMENT

Coordinated execution of concurrent control processes requires adequate means for process management, satisfying technical and physical constraints.

The straightforward approach would be to allow concurrent control processes to be switched on and off independently, mimicking the behaviour of a set of stand-alone controllers. Besides growing technically difficult to operate and thus error-prone with the number of processes involved, such a strategy would disregard an important fact: the controlled quantities are coupled by the plasma and only few combinations of processes refer to realistic physical discharge scenarios.

The latter aspect corresponds to the view of the designated

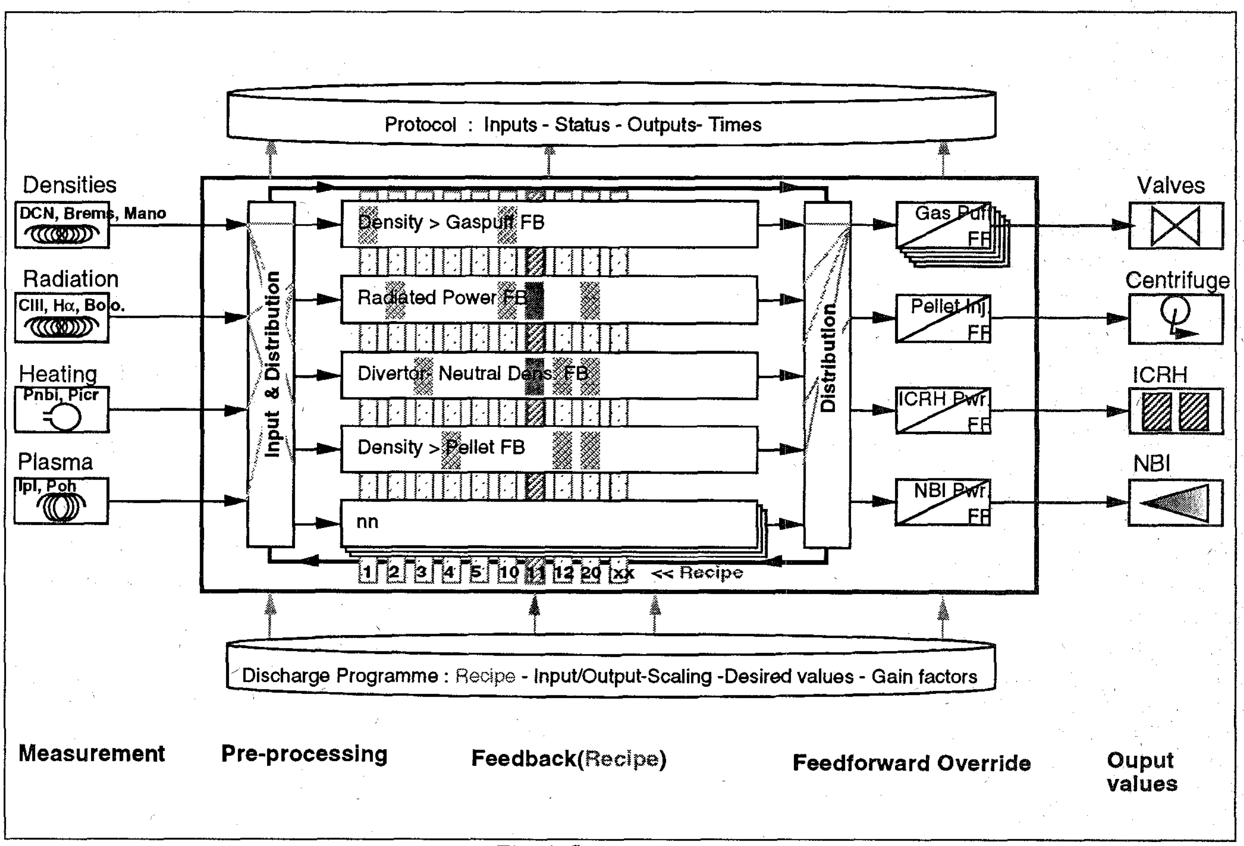


*Fig. 4: Software strucutre*

users of the controller tool: the physicists. When designing a discharge, they think in terms of a sequence of physical scenarios, e.g. ramp-up, cold divertor mode, radiating boundary, H mode stabilization, rather than in terms of the technical details involved. A scenario is characterized as a region in a phase space spanned by specific plasma parameters. The physicist's knowledge enables him to bring the plasma into such a region, given control over a specific subset of these parameters. Such a subset in turn specifies the set of concurrent control and preprocessing algorithms required.

This is the path by which a scenario selects useful configurations from the set of all possible combinations of elementary processes. The same train of thought led us to introduce the concept of globally accessible recipes for managing controller configurations. A recipe defines the state of activity of all elementary control algorithms [Fig. 4].

When the physicist and the software engineer assemble or modify a recipe, the partaking elementary control processes and communication paths are defined. Subsequently, it is checked whether the technical constraints (complete, free of deadlocks and collisions) are met. After the validation, the recipe is considered a valid control configuration and given a unique symbolic name for future reference.

Without loss of flexibility, the recipe concept for process management results in a number of advantages for reliability, operational robustness and transparence. Once a recipe has successfully been assembled, the experimentalist can access and reload it by its symbolic name. A validated recipe inherently avoids the possibility of inconsistent states of the controller during its execution, and its global scope guarantees synchronized action of all active control processes. Furthermore, limiting reconfiguration of the controller to transitions between recipes of a predefined list ensures a coherent controller state at all times.

For operational reasons, such as gas pre-filling, error handling or testing of control loop response and single actuators, it is necessary to have temporary feed-forward access to the actuators. Defining new recipes for this purpose, however, would inflate their number without adding new scenarios. We therefore opted for an override mechanism which allows to switch any actuator into feed-forward mode while maintaining the actual recipe.

## V SYSTEM EMBEDDING

The plasma controller was built from hardware components and software modules used throughout the whole control system. Well-established structures and mechanisms were used, with only minor modifications, to embed the plasma controller into the existing system.

OCCAM code is loaded via the UNIX host interface. When the host starts the code, the plasma controller is linked to the real-time supervisor controller, which takes over. Shot cycle operation is performed in distinct phases: the discharge programme containing the recipes to be executed and reference parameter trajectories is down-loaded and filtered for the required signals [10]. Then a time reset is performed to define a common time base, the clock of which is also provided by the supervisor. With the start of the real-time phase, all controllers begin to execute the discharge programme. If the supervisor controller detects critical technical or plasma states it causes the other controllers to branch coherently to alternate programme sections. After the end of the real-time phase, the controllers contribute their stored measured value and state trajectories to a common discharge protocol.

The plasma controller is connected to the protection system. In machine critical states, e.g. loss of control, this independent system shuts down operation, bypassing the controllers to directly access the actuators. In the less severe case of illegal actual plasma parameter values the supervisor controller initiates a fully controlled, smooth shut-down.

## VI OPERATION EXPERIENCE AND FUTURE DEVELOPMENTS

In the first year of operation, a number of elementary control processes /≈5/ was specified and implemented together with input, preprocessing and output processes. From the possible combinations within this set, only a small fraction /≈10/ was assigned a recipe and actually used.

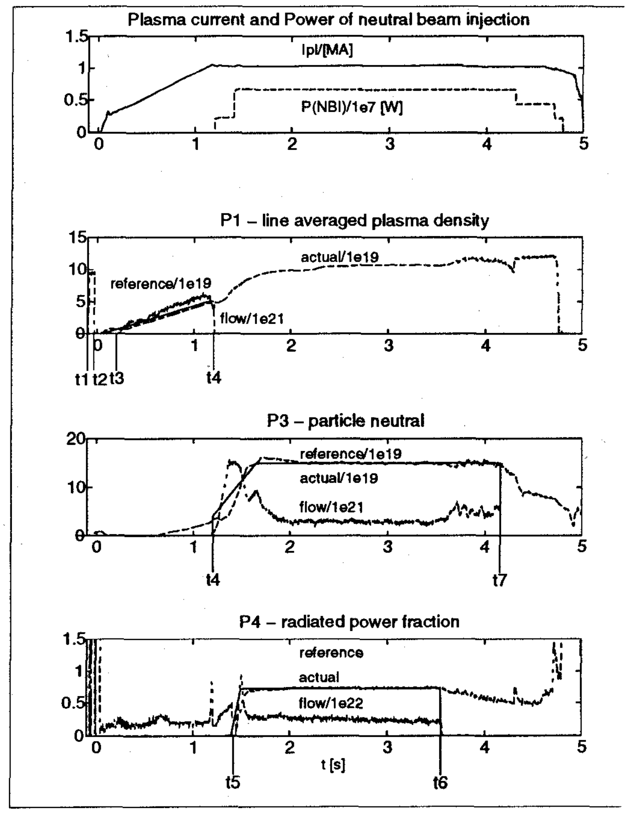


*Fig. 5: Discharge with scenario switching.*

Elementary algorithms now available control:
P1 - line averaged plasma density by gas puffing,
P2 - line averaged plasma density by pellet injection,
P3 - divertor neutral particle flux density by gas puffing,
P4 - radiated power fraction by impurity gas puffing,
P5 - icr antenna coupling by outer contour control.

Some of the recipes defined so far are:
R0 - " stand by " = {}
R1 - " standard density " = {P1}
R2 - " divertor density " = {P3}
R3 - " radiative mantle " = {P3, P4}

An exemplary discharge, aimed at the establishment of an "impurity radiative mantle" scenario, would consist of a sequence like this [Fig. 5]:

Before t1 the controller is initialized to recipe R0. Between t1 and t2, gas pre-fill is done by override feed-forward operation of the gas valves. After changing the recipe to R1 at t3, line density is ramped up under feedback control. At t4, when reaching the flat-top, the recipe is switched to R2 to control the divertor neutral particle flux. At t5, recipe R3 adds control of the radiated power fraction, until at t6 only the divertor control remains with selection of R2. For ramp-down, the recipe is switched to R1 at t7.

To program this sequence, the physicist simply selects 3 recipes from a menu in a graphical user interface, assigns to them appropriate times in the discharge programme, and sets the required reference trajectories for the controller.

From the start of operation, the plasma controller has worked successfully and was found easy to operate. The time needed to implement a new feedback control algorithm or a new recipe into the controller was generally on the order of 2 days, once the specification was written down and validated.

Planned extensions are directed towards the stabilization of H-mode discharges and parameter exchange with shape control.. So far, recipes are scheduled at predefined times. It is desirable, however, to trigger a new recipe at the instance of certain plasma states, e.g. an H-to-L transition.

## VII SUMMARY

At ASDEX Upgrade we look back on one year of successful operation of our multi-purpose plasma parameter controller. The process management concept adopted turned out to be the key to overcome the apparent contradiction between the required high flexibility and ease of operation. The device proved to be an excellent tool for the experimentalist by helping to make better plasmas and taking part in the research progress. The concept of an open, knowledge-based controller platform shows a new trend in fusion oriented plasma control.

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