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Real-time beam tracing for control of the deposition location of electron cyclotron waves

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HIGHLIGHTS

- We successfully integrated a real-time EC beam tracing code at ASDEX Upgrade.
- The calculation of EC beam deposition location is fast enough for control purposes.
- The accuracy of the deposition location calculation exceeds equivalent measurements.
- The implementation method is by design portable to larger fusion devices.

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ABSTRACT

Plasma control techniques that use electron cyclotron (EC) resonance heating and current drive such as control of neoclassical tearing modes require accurate control of the deposition location of EC beams. ASDEX Upgrade has successfully implemented a real-time version of the beam-tracing code TORBEAM into its real-time diagnostic system to act as a globally available module that calculates current deposition location and its sensitivity from other real-time diagnostic measurements for all its moveable EC wave launchers. Based on a highly (100×) accelerated version of TORBEAM, the software implementation as a diagnostic process uses parallelization and achieves cycle times of 15–20 ms for determining the radial deposition location of 12 beams in the plasma. This cycle time includes data input–output overhead arising from the use of available real-time signals. The system is by design portable to other machines such as ITER.

1. Introduction

Real-time control of nuclear fusion plasmas is evolving from simple feedback-control of magnetic coils and single-input single-output feedback control of plasma density toward complex integrated control using multiple actuators with the ultimate goal of optimizing and eventually maintaining high plasma performance. Plasma control systems are starting to make use of multiple real-time measurements and calculate adequate response of the appropriate actuators [1]. One of the most flexible of the currently available actuators is electron cyclotron resonance heating (ECRH) and current drive (ECCD) which have been identified to be useful for a multitude of control tasks such as adjusting density peaking [2], sawtooth control [3–5], disruption avoidance [6] and neoclassical tearing mode (NTM) control ([5,7,8] and references therein).

The paper addresses a software-layer for utilization of real-time controllable EC-wave launchers for the application of control of the ECCD deposition location to active MHD control. After the introduction and presentation of the challenge (Section 2), the paper discusses the relevant code acceleration and validation (Section 3). Its integration into the real-time framework of ASDEX Upgrade with the use of the Message Passing Interface (MPI, [9]) to benefit from modern multi-core CPUs is the topic of Section 4. Section 5 describes the implementation of the ECRH launcher control within the discharge control system (DCS). Section 6 finishes with the conclusions.

1.1. Motivation

Neoclassical Tearing Modes (NTMs) are regularly observed in high performance plasmas at reactor-grade β-values. They severely

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limit the maximal achievable normalized beta β_N, which is undesirable because fusion performance scales as $P_{\text{fusion}} \sim {\beta_N}^2$. NTMs may also lead to disruptions and thus need to be controlled. ASDEX Upgrade has been developing a feedback system for NTM stabilization, which uses real-time mode detection and localization [10]. For that, the ECRH deposition location needs to be accurately aligned with the NTM island. Initially, we followed the idea of measuring the ECCD deposition by modulating the power at frequencies compatible with the required timescales and calculating the deposition location with TORBEAM only as a cross-check at lower time resolution, since the deposition location of a modulated ECRH beam is well measurable in low-confinement plasmas using modulation frequencies below 100 Hz with the ΔT_e modulation above the noise level of the observing ECE diagnostic. However, at higher modulation frequencies and in high power plasmas this could not be realized due to much lower ΔT_e amplitude and ECE diagnostic limitations. The need for an accurate and fast estimate of the ECCD deposition could thus only be satisfied by strongly accelerating the beam-tracing module.

While a potentially simpler system has been demonstrated that measures and actuates in the same reference frame, namely "ECCD based NTM stabilization using inline ECE" [11], that method also has disadvantages. Besides the intrinsic technical difficulties of separating 1 MW of outgoing ECRH power from incoming ECE radiation (at below a few nW), such a system needs to align its typically narrow plasma view with the NTM before it can operate. If a system needs prealignment with rational surfaces, where NTMs may develop, its availability as an actuator for other control tasks is limited at best. Moreover, the inline ECE method is only suitable for active stabilization and cannot be used for preemptive ECCD on rational surfaces. To avoid such a limitation, we have chosen to adopt a more general strategy based on normalized coordinates which also allows to use the same controllers to execute other control tasks by feeding different deposition references as target locations. Since our chosen technique does not preclude the use of inline ECE, e.g. for fine-tuning the deposition location after pre-alignment, this method is also presently investigated at ASDEX Upgrade using the FADIS system [12].

2. Boundary conditions

Throughout the whole paper, coordinates expressed in normalized magnetic flux are based on the poloidal magnetic flux Ψ in the following way:

$$\rho_{\text{pol}} = \sqrt{\left(\frac{\Psi - \Psi_a}{\Psi_s - \Psi_a}\right)}$$

where index s refers to the separatrix (where $\rho = 1$) and index a to the magnetic axis (where $\rho = 0$).

2.1. Code data input and output

TORBEAM [13] needs as inputs the magnetic equilibrium, density and temperature profile as well as a number of parameters describing the initial conditions of the ECRH beam. In order to meet our time-scale requirements, all input data need to be provided with least possible latency. Several real-time diagnostics provide the data to the real-time network, where the real-time TORBEAM process, also called a 'diagnostic' abbreviated as TBM, can access these data [14]. Our implementation makes the TBM process also the master of an MPI domain distributing workload across a number of other processes as required. The output of the real-time TORBEAM version consists of four values for the deposition location coincident with the peak power deposition within the plasma: normalized magnetic flux, radial, vertical and lateral (toroidal offset) coordinate. For receiving and sending real-time data, TBM uses the real-time framework [15] of ASDEX Upgrade and reflective memory as a transport layer for smallest possible latency between itself and the data sources and sinks.

2.2. Why real-time?

If there were no unforeseeable conditions that can change the behavior of our actuator we would not need real-time calculations but could instead use prior knowledge (e.g. look-up tables) and run all actuators in a feed-forward mode. However, this is typically not the case. Experience shows that plasma conditions may change through normal but unwanted or abnormal events that may require immediate intervention for safe operation. When such events occur, too simple models are prone to failure: e.g. strong density peaking which leads to ECRH beam refraction, sawtooth crashes which change core transport on fast timescales, etc. As an indication for the large error that unforeseeable plasma effects can cause, a calculation using TORBEAM was performed, with two density profiles from the same discharge at different, yet not too distant time points $t = 3.1$ s and $t = 3.5$ s. While all other plasma parameters and launching parameters are kept exactly the same, the peak deposition of ECRH power is different for the two cases by approximately 20 cm in vertical direction because of beam refraction (cf. Fig. 1) which equals more than 0.15 in normalized magnetic flux and corresponds to about 8 cm radial distance in the horizontal mid-plane. It is thus clear that by neglecting the density profile it is impossible to know the deposition location to better than several centimeters. While moderate changes in the density profile might still be possible to be prescribed by look-up tables, changes of other parameters such as plasma position, triangularity, etc. must also be accounted for.

Additionally, with respect to generic use of actuators, one piece of hardware (e.g. ECRH/ECCD) is desired for many applications: control of sawteeth, NTMs, density peaking. Thus, a controller that is designed to set launching parameters of the ECRH beam, e.g. by tilting a launching mirror, may be requested to switch between several tasks, each requiring heating power at a different location. Each of those control tasks may have higher or lower priority over the course of long plasma discharges, such that optimizing the controller for one or the other task leaves it less effective or even useless for others. In order to be prepared for all possible (also future, currently unknown) applications, it is necessary to ensure accurate control over the beam and its effect at the deposition location in any possible configuration, which usually depends on the plasma state.

As long as the number of necessary parameters to adequately describe the plasma state can be limited to less than 5, it would be feasible to generate a look-up table with up to 10 values in each dimension that will hopefully cover the full parameter space and hence provide a fast deposition calculation. However, a calculation of such a look-up matrix would already need about 10^5 TORBEAM runs (≈28 CPU hours, assuming 1 s per run). If the number of necessary plasma and machine parameters exceeds 10, even 7 values in each parameter dimension already cost about 60 CPU-years ($\approx 7^{11}$ s). Still, the real-time measurements of the parameters need to be taken and will cause some overhead which grows with size of the look-up table. Thus, in our opinion, it is not sensible to use the look-up table approach. A real-time capable calculation using a physically correct model is the best possible solution at present, especially since the required timescales for the real-time calculation will be less demanding in future larger devices. Moreover, such a solution is by design portable to other machines where the base (TORBEAM) is also operational.