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Institut de Recherche sur la Fusion par confinement magnétique
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Centre de Cadarache, 13108 Saint-Paul-Lez-Durance, France

SUJET DE THÈSE 2023

Titre du sujet

Mesure en temps réel du profil de densité pour le contrôle et l'amélioration des performances des plasmas de WEST

Real-time density profile measurement for the WEST plasma control and performance enhancement

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Résumé du sujet en Français :

La mesure du profil de densité électronique est capitale pour le fonctionnement et l'analyse des plasmas de fusion magnétique. Dans un réacteur, la réflectométrie, une technique micro-onde basée sur le principe du radar, apparaît comme le diagnostic de densité le plus facile à implanter. Toutefois, les mesures de réflectométrie ne sont actuellement traitées qu'après la décharge plasma.
L'objectif est de développer une mesure temps réel du profil de densité puis de l'intégrer au système de contrôle du tokamak WEST pour élargir le domaine opérationnel et améliorer les performances.
Ce développement se fera en adaptant une carte d'acquisition basée sur une puce développée par l'institut d'astronomie et de physique des particules du CEA. Pour accélérer le calcul, l'étudiant(e) réalisera un prétraitement des données avec les ressources de la carte d'acquisition. Les premières applications concernent le contrôle de la densité au bord du plasma : contrôle des flux de particules et du rayonnement, amélioration du couplage de la puissance de chauffage du plasma. D'autres applications pourront être envisagées comme la détection en temps-réel d'instabilités.
L'étudiant(e) sera basé(e) au CEA Cadarache et devra interagir avec les équipes réflectométrie, électronique et acquisition de données, pilotage du plasma. Il/elle acquerra des compétences variées : électronique temps-réel, micro-ondes, contrôle, physique des plasmas. Des collaborations avec des chercheurs en France et en Europe sont aussi prévues puisque cette thèse s'inscrit dans le cadre d'un projet EUROfusion sur le développement de la réflectométrie temps-réel pour le réacteur.

Résumé du sujet en Anglais :

The electron density profile is critical for the operation and physics exploitation of magnetic fusion confinement devices. In a reactor, reflectometry, a microwave technique based on the radar principle, appears to be the easiest density diagnostic to implement. However, reflectometry data are currently processed after the discharge for physics studies.

The PhD objective is to develop a real-time (RT) measurement of the density profile and then to implement it into the WEST tokamak to broaden the operational regime and improve performances. This development will be done by adapting an acquisition card based on a chip developed by the CEA's Institute for astronomy and particle physics. In order to accelerate the density profile reconstruction, the data have to be first pre-processed by the computing resources of the acquisition card. The first applications will focus on the control of the density at the plasma edge: control of particle flux and radiation level, improvement of the coupling of the plasma heating power. Other applications are foreseen such as the RT detection of instabilities, in particular the Edge Localized Modes that trigger/lead to large heat fluxes on the plasma facing components, a major threat for ITER.

The student will be based at CEA Cadarache and will interact with the reflectometry, electronics and data acquisition, and plasma control teams. She/he will acquire a variety of skills: RT electronics, microwaves, control technique and plasma physics. Collaboration with teams in France and in Europe is also foreseen since this thesis is part of a EUROfusion project on the development of RT reflectometry for the reactor.

Formation recherchée / recommandée : Master II en électromagnétisme, radar, traitements du signal ou en physique des plasmas et/ou science de la fusion.

Intitulé du master préconisé :

Description détaillée du sujet :

The accurate measurement of the electron density profile is critically important for the operation and physics exploitation of magnetic fusion confinement devices. However, such measurements with the currently used optical diagnostics (interferometry, Thomson scattering) will be very challenging in a reactor because of issues regarding both optical path implantation and mirror survivability. Conversely, microwave techniques, including reflectometry which is based on radar principle, are more adapted to the harsh environment of a reactor, notably characterized by strong magnetic fields, X-ray radiation and energetic neutrons. Due to their ability to survive and operate in a burning plasma environment, and also to provide a broad-range of key physical data on present devices, reflectometers have recently benefited from a sustained worldwide effort to further develop their measurement capabilities. In particular, this development has reached the level where they can provide routine, highly accurate electron density profile measurements. However, real-time (RT) reflectometry measurements, as required for control applications, are not yet available, and require further developments. Such RT measurements will reveal mandatory in a reactor. In the DIII-D tokamak operated in the USA, the RT measurement of the density profile with Thomson scattering is a key sensor for the RT optimization of the energy stored in the plasma and the RT detection and control of edge instabilities [1]. RT reflectometry would provide density profile with a much better time resolution, close to the cycle time of a few milliseconds of tokamak RT control loop. With this time resolution, RT reflectometry could help to detect the instability precursor based on the increase of the density fluctuations in the early phase of the instability onset.

The aim of the thesis is the development of RT reflectometry profile measurements that could subsequently be used for plasma control on the WEST tokamak operated at CEA Cadarache. Currently on WEST, three reflectometers measure routinely the density profiles within a few microseconds. The edge [2] and core reflectometers [3] provide a measurement of the whole profile. The Radio Frequency antenna reflectometer can be implemented in Lower Hybrid or Ion Cyclotron Resonant Heating (ICRH) antennas and it measures the density profile in the antenna mouth for RF heating coupling studies [4]. The measurement are currently processed after the discharge for post-pulse physics exploitation.

To perform RT measurements, the overall time to acquire, transfer and process the data should be of the same order as the 1 millisecond refresh cycle of the RT control system on WEST. Unfortunately, the current reflectometer hardware and electronic acquisition boards do not allow for RT data transfers. A first step will be to restructure the instrument in order to achieve near continuous data acquisitions in RT. The team has recently gained some expertise in this field with the successful design of the digitizers for the upcoming Thomson Scattering diagnostic on WEST. The proposed solution is based on the Nectar chip [5] which provides a triggered acquisition at a sampling rate in the range 800 MS/s (megasample per second) to 3 GS/s with a depth of 1024 samples. The so-called Nectarine board designed at the Electronics and data Acquisition group at IRFM holds three Nectar chips (i.e. six input channels). It holds also an up-to-date system on chip that integrates the software programmability of a processor with the hardware programmability of an FPGA (Field Programmable Gate Arrays) for Nectar control and readout as well as networking thanks to custom embedded firmware and software. This board provides a good starting point to investigate real-time hardware and firmware accelerated algorithms for density profile reconstruction. For instance, in addition to Nectar readout, the FPGA could be used to perform some more or less basic data processing operations to speed up profile reconstruction. This could lead to devising more complex hardware architectures with chained or interlaced Nectar chips that could offer greater memory and performance.

The other leg of the project is a speedy and reliable profile reconstruction algorithm. Porting the current off-line processing software onto the programmable resources available both on the acquisition board and the reflectometer read out PC is a reasonable first step in speeding-up the inverse problem of profile reconstruction. As the density profile will be used for real-time plasma control, the profile reliability will be a stringent issue so that criteria for the RT detection of physically irrelevant reconstructed profiles will be investigated as well. To further speed-up the reconstruction and to integrate other diagnostics for enhanced accuracy/reliability (e.g. line integrated density from the interferometry diagnostic) neural network or deep learning tools could provide advanced data processing.

The first application of this RT development will focus on the control of the density at the plasma edge. Currently, only the line averaged density is measured in RT. RT density profiles would enables to control the edge density independently of the line average density. Indeed, the edge density governs critical physical issues, most notably the divertor operation regime. The divertor is a dedicated plasma facing component designed to withstand very high heat fluxes. At low edge density, a large fraction of the outgoing plasma energy flows to the divertor. As density increases, a higher fraction of the energy is radiated. Above a threshold, the energy flux on the divertor target drops, the plasma is detached from the divertor and most outgoing energy is radiated. However, this detachment regime is prone to radiation instabilities and sudden reattachment. A RT measurement of the edge density profile would allow one to operate with a high divertor radiation fraction - mandatory to reduce the heat flux on the divertor in a reactor [6] - below the detachment regime and the associated instabilities.

Maximizing the coupling of the heating power to the plasma is another application of RT reflectometry. WEST plasmas are heated by RF antennas. The coupling of the power is governed by the density profile in front of the RF antenna. The antenna reflectometer would enable the control of the profile in front of the antenna to increase the coupling fraction and hence WEST performances.

The candidate will work at Institute for Magnetic Fusion Research (IRFM) at CEA Cadarache. She/he will be supervised by Y. Moudden (Electronics and data Acquisition group) and R. Sabot (experiment, heat and particle control group). She/he will interact with the various IRFM teams: reflectometry, electronics and data acquisition, plasma control. Collaborations with French, Portuguese and Italian teams are also planned as the PhD is part of a EUROfusion Enabling Research project “Advances in real-time reflectometry plasma tracking for next generation machines: Application to DEMO”.

[1] F.M. Laggner, et al, *Real-time pedestal optimization and ELM control with 3D fields and gas flows on DIII-D*, Nucl. Fusion. 60 (2020) 076004.

[2] F. Clairet, et al, *1 µs broadband frequency sweeping reflectometry for plasma density and fluctuation profile measurements*, Review of Scientific Instruments. **88** (2017) 113506.

[3] R. Sabot, et al, *Development of Microwave Imaging Diagnostics for WEST Tokamak*, J Fusion Energ. (2019).

[4] C. Bottereau et al. *New reflectometer in a low hybrid launcher on Tore Supra,* 10th Int. Reflectometry Workshop, Garching, 2011

[5] C.L. Naumann, E. Delagnes, J. Bolmont, et al. *New electronics for the Cherenkov Telescope Array (NECTAr)*. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, **695**:44–51, 2012.

[6] S.I. Krasheninnikov, et al, *Divertor plasma detachment*, Physics of Plasmas, **23** (2016) 055602.

Collaborations scientifiques et/ou partenariats industriels envisagés :

- Nom du collaborateur: Filipe Da Silva
- Organisme/Société: Institute for Plasmas and Nuclear Fusion in Lisbon
- Raison de la collaboration: Filipe Da Silva is the Principal Investigator an EUROfusion Enabling Research focused on reflectometry development for DEMO, the European reactor step. The project covers several aspects including profile accuracy and reliability, Real-Time development and time synchronization of multiple reflectometers.