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Progress on the ITER ECRH upper launcher steering mirror identification and control

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ABSTRACT

The main objective of the ITER ECRH upper launcher (UL) is to control magnetohydrodynamic activity, in particular neoclassical tearing modes (NTMs), by driving several MW of EC current near the $q = 1$, 3/2, 2 flux surfaces, where NTMs are expected to occur.

The steering of the EC power is done by the steering mechanism assembly (SMA) that comprises a reflecting mirror and a frictionless and backlash free pneumo-mechanical system actuated with pressurised helium gas. The control requirements for this component in terms of steering accuracy and speed are reviewed. With respect to these requirements, the performance of the first SMA prototype is assessed in a mock up of the UL pneumatic configuration.

The expected design characteristics of the SMA have been verified and an overall satisfactory performance has been assessed. Furthermore, the main challenges for the future work, such as the pressure and angular position control, have been identified.

1. Introduction

The main objective of the ITER electron cyclotron resonance heating (ECRH) upper launcher (UL) is to control magnetohydrodynamic (MHD) activity, in particular neoclassical tearing modes (NTMs). The UL is located in 4 of the 16 upper ports (8×1 MW beams at 170 GHz per port) [1].

The use of EC power to control NTMs and MHD in tokamaks has been largely studied in theory and in existing machines and scaled to ITER [2–8].

To maximise the NTM stabilisation performance, the quasi-optical layout of the UL is designed so that the beams are oriented and properly focused to obtain a maximum overlapping of the waists of all the beams throughout the deposition location range in the plasma.

Fig. 1 shows how the steering of the beams is done in the front part of the UL using two independent steering mechanism assemblies (SMAs). Each SMA consists of a mirror and a frictionless and backlash free mechanical system that is pneumatically actuated using helium to provide adequate angular positioning of the mirror [9,10].

The precision at which the beams are launched into the plasma at the adequate location is crucial for the success of the system. This depends on the determination of the required deposition location, and thus, the required steering angle [11,12], subject not treated in this paper. Once the required steering angle is determined, it is crucial that the SMA can be controlled to satisfactory accuracy and speed in order to deliver the required angle, subject treated in this paper.

Section 2 reviews the steered angle control requirements and Section 3 presents the SMA and the test stand at the Centre de Recherche en Physique des Plasmas (CRPP) in Lausanne (Switzerland), used to perform the identification and control tests.

The characterisation and modelling of the SMA are described in Section 4 and the corresponding controller design and results are presented in Section 5.

Section 6 summarises the results and outlines the main challenges for the work in the future.

2. Required performance

The UL has to ensure that all the EC power launched into the plasma is focused at the 170 GHz resonance surface at the $q = 3/2$ and $q = 2$ magnetic flux surfaces where NTMs are expected to occur in ITER [13], or in the $q = 1$ surface for sawtooth control [2], throughout its operation.

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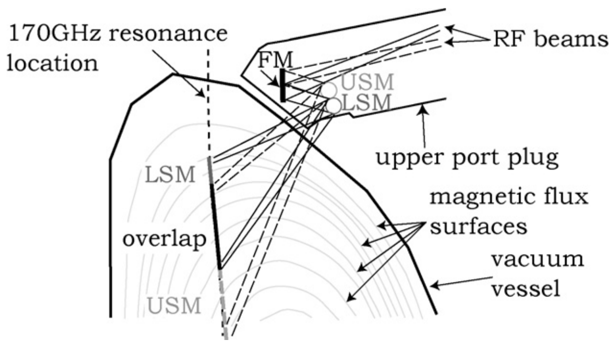

Fig. 1. Schematic view of the top part of a cross-section of an ITER plasma with the front part of the front steering UL port where the focusing (FM) and steering mirrors are used for conditioning the beams going into the plasma. The steering range access of the upper steering (USM) and lower steering (LSM) mirrors are illustrated.

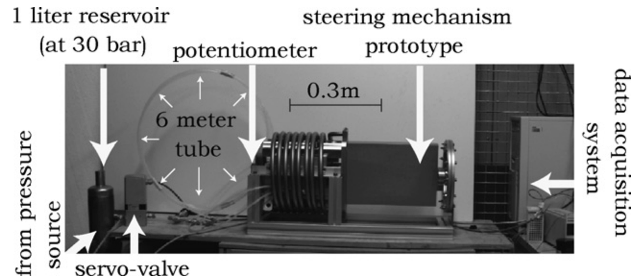

Fig. 2. Set-up of the SMA first prototype for testing in a mock-up of the configuration in the port plug at the Centre de Recherce en Physique des Plasmas in Lausanne, Switzerland. A 1 l reservoir at 30 bar is connected as a pressure buffer between the gas source and the servo-valve (SV). The valve is connected to the SMA by a 6 m tube. The angle of the SMA is measured by a commercial potentiometer, and the control and data acquisition are done using virtual instruments on a standard PC.

The $q = 1, 3/2, 2$ flux surfaces are expected to occur in the $0.3 \leq \rho_{tor} \leq 0.86$ range for different ITER plasma scenarios ($\rho_{tor} = \sqrt{\text{normalised toroidal magnetic flux}}$). The EC power will be launched from the upper steering mirror (USM) or from the lower steering mirror (LSM). As shown in Fig. 1, the USM accesses the $0.3 \leq \rho_{tor} \leq 0.8$region, and the LSM accesses the $0.6 \leq \rho_{tor} \leq 0.86$region, this corresponds to a steering of the beams of $\pm 11^\circ$ translating to $\pm 5.5^\circ$ of mirror rotation [1].

The SMA is required to cover the entire steering range within a fraction of the mode growth rate, which is estimated to be in the order of 10–20 s [14]. This corresponds to the worst case scenario, where the beams are aimed at one end of the steering range and their deposition is required at the other end.

Once the EC power is directed to the desired location, a small modulation of beams in the range of $\pm 3.8^\circ$ ($\pm 1.9^\circ$ of mirror rotation) will be required in order to follow the magnetic flux surface assuming variations in the plasma pressure and internal inductance [13,15], that are expected in a 1–5 s time scale [14].

The deposition on the plasma is required to be accurate to $\leq$10 mm so that the beam and the NTM have a sufficient overlap [16]. To meet this requirement, a precision of the steering angle $\leq 0.1^\circ$ for the mirror steering angle is required [1], and the design target accuracy is $\leq 0.025^\circ$.

In terms of system reliability, the SMA is expected to run flawlessly throughout the life of ITER. This has been estimated to 2.1×10^4 full range cycles and 8.4×10^5 small modulation cycles [15]. A test program for the manufacturing of prototypes of the critical components and testing them in working conditions expected in the ITER is currently taking place and will continue throughout the 2008–2010 period to ensure an adequate build to print design of the UL [17–19].

3. System description

The pneumo-mechanical system of the SMA consists on four externally pressurised bellows working against six pre-loaded compressive springs. Two flexure pivots are used instead of traditional bearings, which makes the mechanism friction free, eliminating stick-slip and backlash. Additionally, cold welding and other in-vessel tribological difficulties due to the harsh environment (heat, neutron radiation from the plasma) are avoided [10,20,21]. Because of these characteristics, the SMA is expected to have an excellent linear relation between the applied pressure and the resulting steering angle.

The steering range is $\pm 7^\circ$ for a pressure range of 0.3–2 MPa. The additional $\pm 1.5^\circ$ with respect to the required $\pm 5.5^\circ$ steering range (cf. Section 2) will be used for compensating misalignments due to assembly and manufacturing precision, deformation of the port plug during operation and other sources of misalignment [22].

The actuation is done by pressurised helium regulated by a pneumatic servo-valve (SV). Helium is used as the actuation gas because of its high acoustic velocity (= 1170 m/s at 393 K) similar to oil (= 1390 m/s), and much higher than that of air (= 400 m/s at 393 K). Besides, in case of a leak, since helium is already present in the vacuum vessel, it would not contaminate the vessel as other transfer media would.

A first prototype of the SMA designed at the CRPP [23] has been constructed by an industrial partner. This prototype has been built as proof of principle of the mechanism. A second SMA prototype, that will be more compatible with the operating conditions for this type of components in ITER, is currently being constructed [18].

In the UL configuration, the SMA is 6 m away from the SV, which is placed outside the port cell. This configuration has been reproduced for performing the tests by adding a 6 m tube between the SMA prototype and the SV, as shown in Fig. 2.

4. Analysis and identification

The SMA prototype system has been analysed in terms of rigidity and fundamental resonance frequency and dynamic response in order to characterise the requirements for a suitable control system, a suitable SV and to develop control algorithms that meet the performance requirements described in Section 2.

4.1. Static characteristics

The required pressure control accuracy is $\delta p \leq \delta\alpha(\Delta p/\Delta\alpha) = 3.0$ kPa, calculated from the pressure range $\Delta p = 1.7$ MPa and the steering range $\Delta\alpha = 14^\circ$ given the desired angular accuracy $\delta\alpha \leq 0.025$.

The theoretical rotational rigidity of the SMA prototype $C_{m,th}$, calculated from the pressure range Δp with total active surface of the bellows S_a and the distance of the bellows to the rotation axis (lever arm) l_b for the steering range $\Delta\alpha$, is

$$C_{m,th} = \frac{\Delta p S_a l_b}{\Delta\alpha} = 1.1 \times 10^3\ \text{Nm rad}^{-1}, \qquad (1)$$

which is within 6% agreement with the measured rigidity $C_{m,meas} = 1.23 \times 10^3$ Nm rad^{-1} calculated from Fig. 3. This is considered good since, for instance, the rigidity of the compressive springs is known to 10%. Note that for the next prototype and the SMAs that will go into the UL, all the components will be fully characterised in working conditions to assess the evolution of their properties throughout the operation of the machine.