Development and installation of a scintillator based detector for fast-ion losses in the MAST-U tokamak

J.F. Rivero-Rodriguez[1,2], M. Garcia-Munoz[2,3], L. Sanchis[2,3], R. Martin[4], K.G. McClements[4], R.J. Akers[4], A. Snicker[5], J. Ayllon-Guerola[1,2], J. Buchanan[4], P. Cano-Megias[2,6], J. Galdon-Quiroga[2,3], D. Garcia-Vallejo[1], J. Gonzalez-Martin[1,2], the MAST Upgrade Team and the EUROfusion MST1 Team*

[1] *Department of Mechanical Engineering and Manufacturing, University of Seville, Spain.*

[2] *Centro Nacional de Aceleradores (CNA) (Universidad de Sevilla, CSIC, Junta de Andalucia).*

[3] *Department of Atomic, Molecular and Nuclear Physics, University of Seville, Spain.*

[4] *CCFE, Culham Science Centre, Abingdon, Oxon, OX13 3DB, UK.*

[5] *Aalto University, Department of Applied Physics, P.O. Box 14199, FI-00076.*

[6] *Department of Energy Engineering, University of Seville, Spain.*

Introduction

In magnetically confined fusion devices, fast-ions play a crucial role in plasma heating and non-inductive current drive. Moreover, their loss can damage the stricken plasma facing components of the reactor. Fast-ion losses can be enhanced by the MHD activity of the plasma, such as Alfvén eigenmodes or Edge Localized Modes [1, 2, 3], or externally applied magnetic perturbations [4], among other causes. Therefore, understanding and monitoring the fast-ion losses is necessary to achieve a good plasma performance.

A novel Fast-Ion Loss Detector (FILD) [5] has been designed and recently installed [6] at the MAST-U spherical tokamak [7]. FILD is a unique diagnostic in the detection of escaping fast-ions, inferring their velocity-space and fluctuations. It uses a scintillator and the tokamak magnetic field to work like a magnetic spectrometer. Since spherical tokamaks can perform a broader range of plasma q_{95}, the MAST-U FILD combines for the first time a rotary and a reciprocating system to adapt its orientation to the plasma q_{95}.

In this work, the characterization of the fast-ion population has been carried out to estimate the FILD signal on a MHD quiescent plasma target for MAST-U (2 MA, 0.75 T, double-null plasma). This has provided useful information to the design of the FILD rotary and reciprocating system, which is also presented here.

*See the author list of *Overview of progress in European Medium Sized Tokamaks towards an integrated plasma–edge/wall solution* by H. Meyer et al., Nucl. Fusion **57** 102014 2017.

NBI birth profile

The MAST-U fast-ion population is generated by two Positive Ion Neutral Injectors (PINI), providing 2.5 MW each, at a maximum injection energy of 75 keV. One injector (South, SS) is placed on the midplane (on-axis) and the other (South-West, SW) is placed 650 mm above the midplane (off-axis).

The MAST-U PINI geometries have been included in the BBNBI code [8] to calculate the ionization profile. The geometry of each injector is defined from the holes of their grounded grid. The horizontal focal length of both injectors is 14 m and the vertical focal length is 6 m.

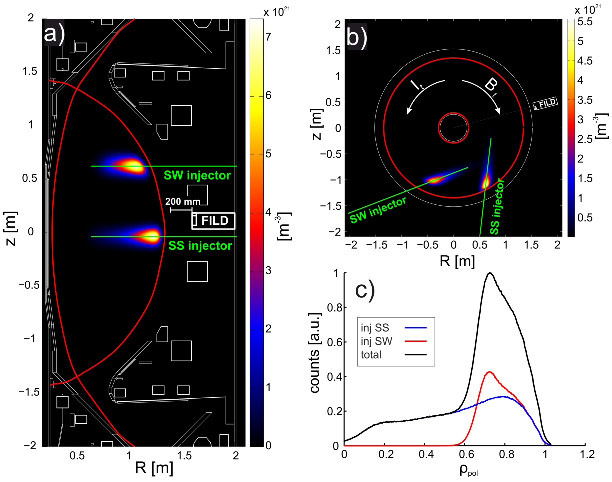

Figure 1: *(a) Poloidal and (b) toroidal cross-section of the beam deposition in MAST-U. (c) Densities of ionized beam neutrals from the on-axis PINI (blue), off-axis PINI (red) and total (black).*

Figure 1(a) and 1(b) show the estimated beam deposition of the SS and the SW PINI. Figure 1(c) illustrates the densities of ionized beam neutrals for each injector as a function of the radial coordinate ρ_{pol}, showing that the use of the off-axis injector increases the fast-ion density at the edge of the plasma. The shine-through of the SS injector is P_{st} = 695 W, mainly impinging on sector 2, and the SW injector is P_{st} = 7120 W, hitting the upper part of sector 4. Thus, the total shine-through power is P_{st} = 7815 W, 0.16% of the nominal injected power.

Orbit following simulations

The MAST-U NBI-birth fast-ions have been simulated with the orbit following code ASCOT [9]. In these simulations, the fast-ions reaching the FILD head can be considered an estimation of the prompt losses resulting from the NBI heating.

The simulations use 5 million markers that are followed until they collide with any element of the MAST-U wall (including the FILD probe) or they are followed a maximum time of $t = 10^{-4}$ s. A sampling on the FILD insertion, labelled in Fig. 1(a), has been carried out, displaying that FILD will detect fast-ions in the insertion range between $R = 1.4$ m and $R = 1.5$ m. The fast-ion power impinging on the FILD probe is 357 W when it is fully inserted, as shown in Fig. 2(a).

Two different fast-ion distributions strike the FILD probe each one corresponding to one of the injectors. The fast-ions produced by the injector SS that reach the FILD probe are (E = 75 keV, $\Lambda = 73^o$), whereas the fast-ions produced by the injector SW are (E = 75 keV, $\Lambda = 54^o$).

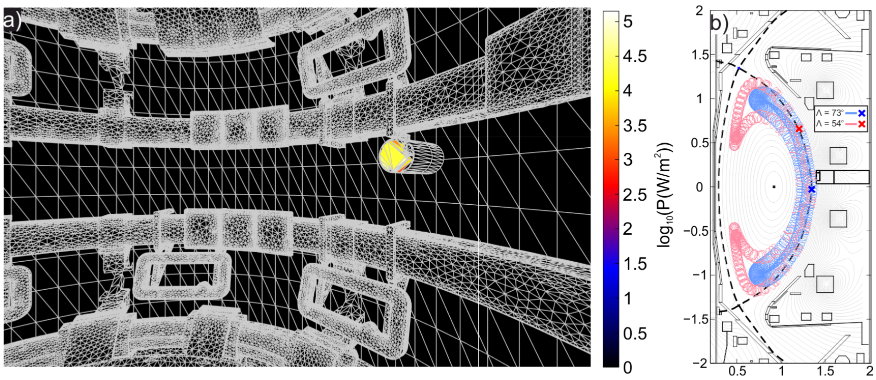

Figure 2: *(a) 3D view of the power load on FILD at* $R = 1.4$ m *insertion. (b) Poloidal view of the two types of fast-ion orbits reaching the FILD probe and their initial position.*

The orbits followed by the two distributions striking the FILD probe are shown in Fig. 2(b).

The MAST-U FILD

The MAST-U FILD is unique in that it combines a rotary and a reciprocating system that drives the probe head in a shot-to-shot basis, as shown in Fig. 3(a), making it possible to adapt its aperture orientation and radial position to the plasma q_{95}. It is a especially important feature in a spherical tokamak since they can perform a broad range of plasma q_{95}.

The probe head and the collimator are designed so that the detector range covers the three NBI energy components (75 keV, 37.5 keV and 25 keV) with a good signal resolution. The resolution in pitch angle is estimated to be $\Lambda = \pm 2^o$ in the entire velocity-space range covered by FILD. The resolution in energy depends on the energy value, being $E = \pm 16$ keV at the maximum injection energy.

The detector geometry and the scintillator properties are used in the FILDSIM code [10] to produce a synthetic frame of the fast-ion velocity-space hitting the FILD probe, previously estimated with ASCOT. The strike map is constructed assuming that the collima-

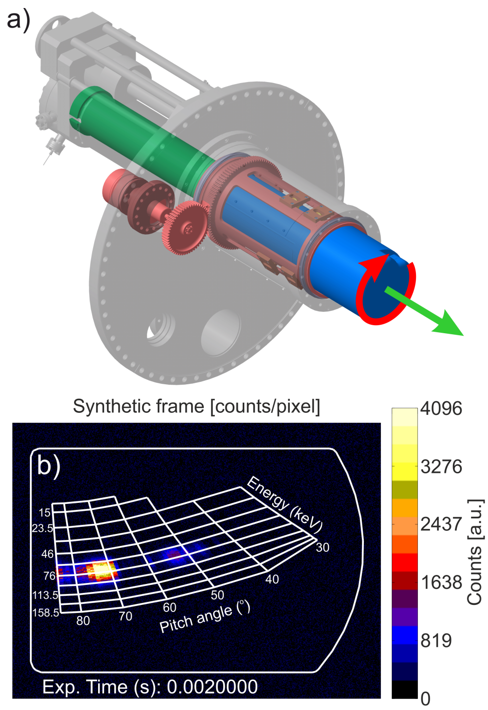

Figure 3: *(a) Rotary (red) and reciprocating (green) system that drives the FILD probe head (blue) [6]. (b) Synthetic FILD frame for the impinging fast-ions velocity-space at a insertion of* $R = 1.4$ m.

tor aperture is aligned to the magnetic field lines and the magnetic field at the FILD probe is $B = 0.63$ T. The synthetic frame, illustrated in Fig. 3(b), shows two separate spots on the strike map. Each spot corresponds to one of the injectors fast-ion population thus showing good resolution to separate both contributions.

Summary

The first MAST-U FILD is now designed and installed. Its rotary and reciprocating probe makes possible to adapt its aperture orientation and radial position for a broad range of plasma scenarios. The detector geometry is designed so that it has good energy and pitch angle resolution to detect the NBI-birth fast-ion losses.

The neutral beam ionization code BBNBI and the orbit following code ASCOT have been used to estimate the fast-ion velocity-space reaching the FILD probe in a MHD quiescent plasma target for MAST-U. This has made possible to construct a synthetic frame, showing that the contribution of the on- and off-axis NBIs form separate spots on the FILD signal.

These results will be used during the diagnostic commissioning, as a reference to infer the fast-ions velocity-space from the experimental results. Further work will require including perturbative effects to fast-ion modelling, such as externally applied magnetic fields and MHD fluctuations, in order to study their effect on the fast-ion transport in MAST-U.

Acknowledgement

This research received funding from the V Plan Propio de Investigación de la Universidad de Sevilla (PP2016-7145). The simulations were partly performed on the MARCONI supercomputer (CINECA). This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under Grant Agreement No. 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

References

[1] A. Fasoli et al. *Phys. Rev. Lett.*, 76(7):1067–1070, 1996.
[2] M. García-Muñoz et al. *Phys. Rev. Lett.*, 100(5):1–4, 2008.
[3] J. Galdon-Quiroga et al. *Phys. Rev. Lett.*, accepted, 2018.
[4] M. García-Muñoz et al. *Plasma Phys. Controlled Fusion*, 55(12):124014, 2013.
[5] M. García-Muñoz et al. *Rev. Sci. Instrum.*, 80(5):053503, 2009.
[6] J.F. Rivero-Rodriguez et al. *Rev. Sci. Instrum.*, accepted, 2018.
[7] A W Morris. *IEEE Trans. Plasma Sci.*, 40(3):682–691, 2012.
[8] O. Asunta et al. *Comput. Phys. Commun.*, 188(2015):33–46, 2014.
[9] E Hirvijoki et al. *Comput. Phys. Commun.*, 185(2014):1310–1321, 2014.
[10] J. Galdon-Quiroga et al. *Plasma Phys. Controlled Fusion*, submitted, 2018.