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

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

\textsuperscript{1} Department of Mechanical Engineering and Manufacturing, University of Seville, Spain.
\textsuperscript{2} Centro Nacional de Aceleradores (CNA) (Universidad de Sevilla, CSIC, Junta de Andalucia).
\textsuperscript{3} Department of Atomic, Molecular and Nuclear Physics, University of Seville, Spain.
\textsuperscript{4} CCFE, Culham Science Centre, Abingdon, Oxon, OX13 3DB, UK.
\textsuperscript{5} Aalto University, Department of Applied Physics, P.O. Box 14199, FI-00076.
\textsuperscript{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 \cite{1, 2, 3}, or externally applied magnetic perturbations \cite{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) \cite{5} has been designed and recently installed \cite{6} at the MAST-U spherical tokamak \cite{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.

\textsuperscript{*}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 \textbf{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) 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 $\rho_{pol}$, 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\( (E = 75\, \text{keV}, \Lambda = 73^\circ) \), whereas the fast-ions produced by the injector SW are \( (E = 75\, \text{keV}, \Lambda = 54^\circ) \).

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 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 \( \Lambda = \pm 2^\circ \) in the entire velocity-space range covered by FILD. The resolution in energy depends on the energy value, being \( E = \pm 16\, \text{keV} \) at the maximum injection energy.

The detector geometry and the scintillator properties are used in the FIELDSIM 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-
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.

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**References**