Observations of confined fast ions in MAST-U with the NCU

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Introduction

Spherical tokamaks contribute to the design of future fusion reactors in several key areas such as divertor physics, neutral beam current drive and Fast Ion (FI) physics. MAST-U, which was designed to address, among other objectives, these issues, has successfully concluded its first experimental campaign (MU01) providing a wealth of new results. Thanks to its low magnetic field (< 1 T) and high energy (> 50 keV) of the NBI system, MAST-U is suitably poised to study the interaction of super-Alfvénic FIs with a wide range of MHD instabilities including global ones determined by the plasma scenario such as sawteeth (ST), NTMs and ELMs as well as broad categories of Alfvén instabilities such as TAEs, GAE and CAEs and of energetic particle modes such as fishbones (FBs). To further explore the role of the FI distribution function spatial gradient in driving these instabilities, MAST-U is equipped with two tangential NBI systems, one on the equatorial plane (on-axis) and one that is vertically shifted 65 cm above the equatorial plane (off-axis). In order to study the rich physics that was expected, and confirmed in the recent experimental campaign, several FI diagnostics were upgraded and new ones added. Among them, the prototype neutron camera [1] has been upgraded [2] to six sight-lines (all on the equatorial plane as shown in figure 1). One key improvement of the Neutron Camera Upgrade (NCU), in addition to those detailed in [2], has been the suppression of the detection of the 2.2 MeV γ-rays generated by the thermal neutron capture in the polythene shielding as shown in figure 1. This resulted in a lower load on the data acquisition system as well as an improvement in the pulse shape discrimination between neutron and γ-rays events.

On-axis and off-axis neutral beam injection

Detailed study of on-axis and off-axis NBI heating in MAST, in which both NBI systems were injecting FI on-axis, showed that the FI confinement was improved in Single Null Divertor (SND) configuration with the magnetic axis vertically shifted downwards by approximately 15 cm from the midplane of the vacuum vessel compared to standard Double Null Divertor (DND) operations with the magnetic axis in the machine midplane [3]. In this study it was observed that operation in the SND configuration resulted in broader FI deposition profiles with a doubling of the neutron rate when the input NBI power was doubled from 1.5 to 3.0 MW, compared to DND scenarios where doubling the NBI power resulted in only a 30 % increase in the neutron rates.

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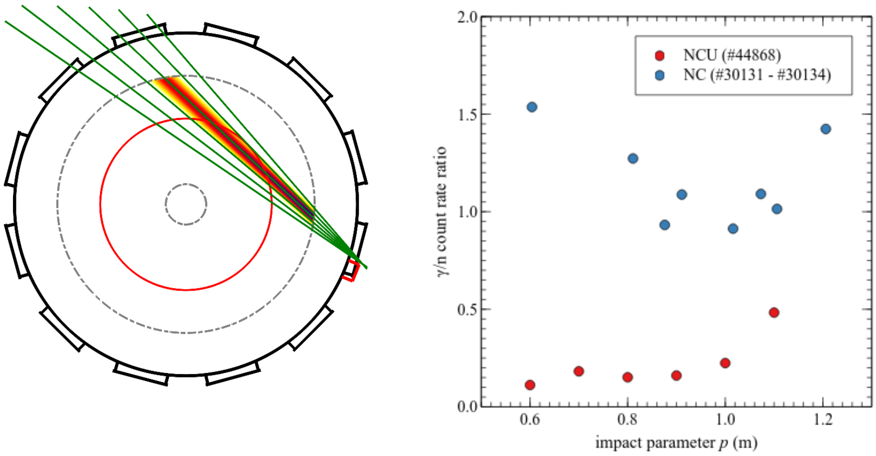

Figure 1: Left panel: top view of the NCU sightlines (green), the typical magnetic axis (in red) and LCFS in/outboard location (dashed gray lines). The color map shows the solid angle calculated by LINE2 for one sight-line. Right panel: γ-ray to neutron count rate ratio for the prototype NC and the NCU as a function of the impact parameter.

The FI anomalous diffusion coefficient needed to reproduce the measured neutron rates was reduced from typical values of ≈ 2.5 m^{2}s^{-1} in DND to ≈ 0.5 m^{2}s^{-1} in SND. This improvement is well understood in terms of the reduction of the radial gradient of the FI distribution function which usually provides the dominant FI drive of modes with frequencies up to around the TAE range [4]. In order to reduce FI redistribution due to TAEs and EPMs and for efficient NBCD, MAST-U was operated with one on-axis and one off-axis NBI system each capable of delivering 1.5 MW with energies between 65 and 75 keV. The predicted peaked and hollow FI profiles in

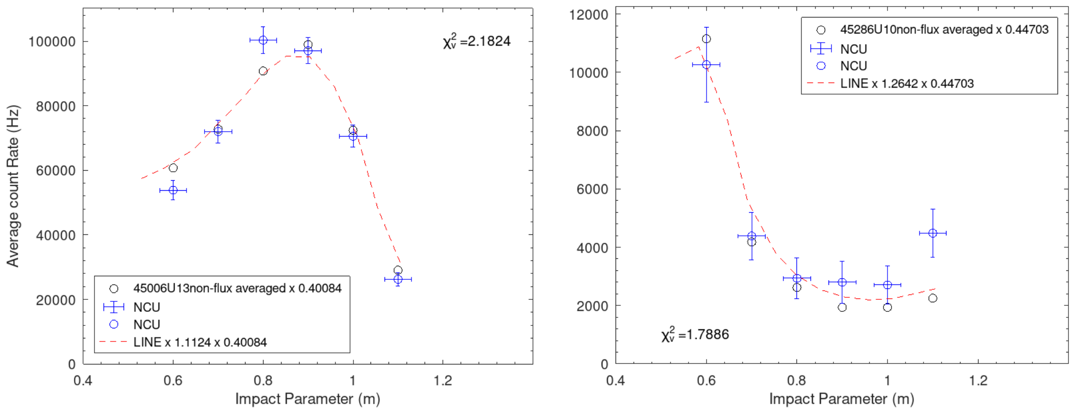

Figure 2: Neutron count rate profiles for on-axis NBI (left panel, #45006 at t = 350 ms) and off-xis NBI only (right panel, #45286 at t = 700 ms) compared with TRANSP predictions using analytical calculations (open black circles) and LINE2 solid angles (dashed red lines).

MAST-U with on-axis and off-axis NBI heating [5] have been experimentally confirmed as shown in figure 2 where the collimated neutron count rate profile measured by the NCU is compared with the predicted using TRANSP. In both TRANSP simulations no FI anomalous fast ion diffusion was assumed (both plasma discharges showed low level of MHD activity) and the predicted profiles were obtained using the non-flux averaged neutron emissivity [6]. In both cases, a scaling factor of ≈ 0.42 is necessary to match them to the absolutely calibrated NCU measurements. This scaling factor is not too different from the one observed in MAST [7] and it is likely linked to the guiding centre approximation used in NUBEAM [8] not being exactly applicable to spherical tokamaks. It is worth noting that in the off-axis case, the neutron rates measured by the NCU are approximately a factor 10 lower than in the on-axis case for the same NBI input power suggesting much lower confinement of the FIs from the off-axis NBI. A partial explanation might be due to the plasma elongation in MU01 ($\kappa \approx 2$) being lower than the target values for MAST-U scenarios ($\kappa \approx 2.5$) resulting in off-axis FI being born close to the LCFS which, combined with large Larmor radii and orbits width make them susceptible to prompt CX losses. This will be investigated in the upcoming experimental campaign where the operational space of MAST-U will be extended to higher elongations.

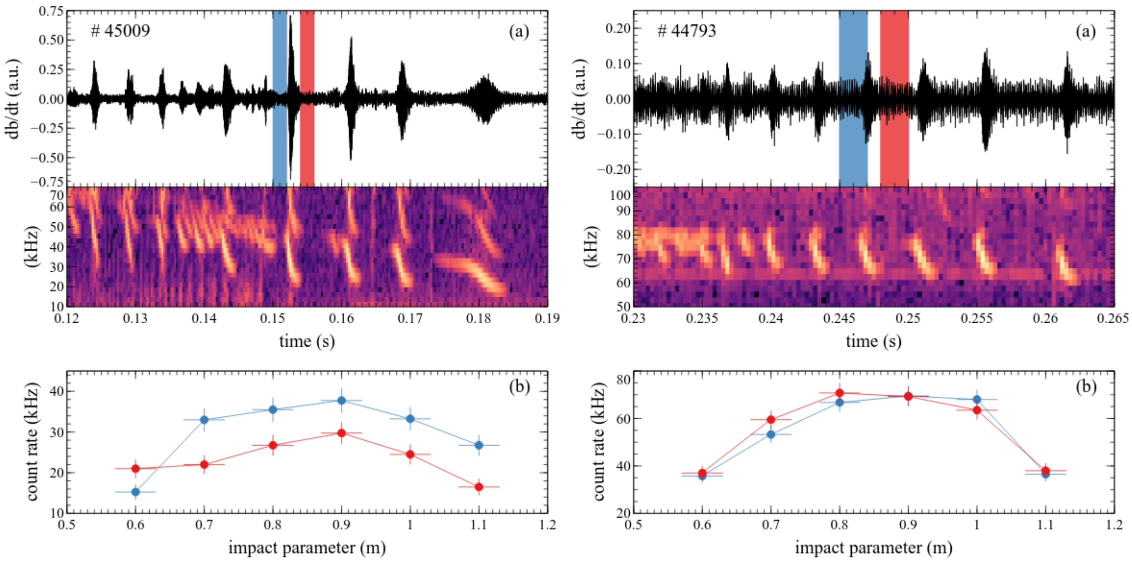

Figure 3: Left: panel (a) FBs evidence in the OMAHA pick-up coil signal and spectrogram; panel (b) FI losses due to the FB in the time interval indicated by the colored regions in panel (a). Right: panel (a) TAEs evidence in the OMAHA pick-up coil signal and spectrogram; panel (b) FI redistribution due to the TAEs in the time interval indicated by the colored regions in panel (a).

Fast ion redistribution and losses

During MU01, TAEs, FBs and ST were observed to cause redistribution and losses of FI as shown in figures 3. TAEs are commonly observed soon after the start of the on-axis heating, with frequencies in the [70, 100] kHz range and result mainly in the redistribution of FIs. FBs, characterized by frequencies below 40 kHz, are more seldom observed but result in large FI losses. In scenarios with off-axis NBI only neither TAEs nor FBs are observed as a results of a weaker drive mechanism due to smaller gradients in the FI distribution. Figure

3 also highlights the significant improvement of the NCU over the NC, namely the capability of observing TAEs and FBs effect on the FI population at multiple locations for the same plasma discharge (the NC was limited to two impact parameter requiring repeated discharges in which the TAEs and FBs dynamics was never identical). Finally, figure 4 shows the evolution of the collimated neutron count rates during the sawtooth phase of plasma discharge 44789 and the pre- and post-crash profiles for the crash at 534 ms. As expected, the sawtooth is responsible for a large loss of the FI population in the plasma core resulting in the suppression of the neutron emissivity across the whole plasma region. Contrary to MAST, in MAST-U the presence of long-lived modes [9] is not as common. Instead, two additional effects are correlated with a reduced confinement of the FI: *i*) plasma rotation slowing down and *ii*) Neoclassical Tearing Modes (NTMs). In the first case, the neutron rate is observed to decay at the onset of the rotation slowing down and to remain suppressed as the plasma locks to the wall. In the second case, the neutron rate is observed to remain suppressed in the presence of $m/n = 3/2$ NTM with frequencies of ≈ 10 kHz which are typically sustained for a significant fraction of the plasma flat-top phase.

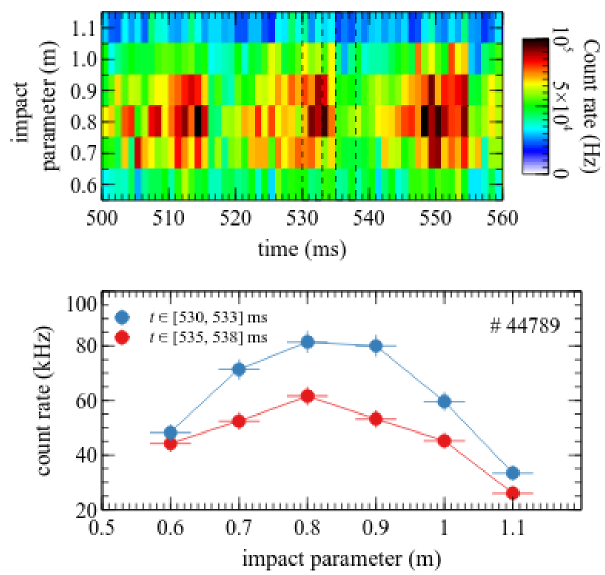

Figure 4: Top panel: time evolution of NCU count rates during ST. Bottom panel: profiles before and after the crash at 534 ms.

Acknowledgments

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References

[1] Cecconello M. et al. *Nuclear Instruments and Methods in Physics Research* **A 753** (2014) 72–83
[2] Cecconello M. et al. *Review of Scientific Instruments* **89** 10I110 (2018)
[3] Turnyanskiy M. et al. *Nuclear Fusion* **53** 053016 (2013)
[4] McClements K. G. and Fredrickson E. D. *Plasma Physics and Controlled Fusion* **59** 053001(2017)
[5] Morris A. W. et al. *IEEE Trans. Plasma Sci.* **42** 402 (2014)
[6] Klimek I. et al. *Nuclear Fusion* **55** 023003 (2015)
[7] Cecconello M. et al. *Nuclear Fusion* **59** 016006 (2019)
[8] Sperduti A. et al. *Nuclear Fusion* **61** 016028 (2021)
[9] Chapman I. T. et al. *Nuclear Fusion* **50** 045007 (2010)