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UKAEA-CCFE-CP(20)71

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This paper has been submitted to
27th IAEA Fusion Energy Conference, Ahmedabad, India, 22-27 October 2018

FAST-ION CONFINEMENT DURING OFF-AXIS NBI IN LOW COLLISIONALITY DISCHARGES AT ASDEX UPGRADE AND TCV

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Abstract

The fast-ion transport has been investigated in low-collisionality discharges at ASDEX Upgrade and TCV using off-axis neutral beams. In both devices Alfvén eigenmode activity was observed which does, however, not strongly affect the global fast-ion confinement. In contrast, charge exchange losses have been identified to have a strong effect. At TCV up to 25% of the injected off-axis neutral beam injection (NBI) heating power is lost by charge-exchange while about 13% of charge exchange losses are observed in ASDEX Upgrade. The impact of charge exchange losses is weaker in ASDEX Upgrade, explained by higher fast-ion energies and a larger minor radius. In ASDEX Upgrade, however, a strong effect of resonant magnetic perturbations (RMPs) on the fast-ion confinement is observed in case of kink-like amplification of the RMP fields. Here, up to 20% of the fast ions are lost which agrees which modelling results.

1. INTRODUCTION

Steady-state operation of fusion devices based on the tokamak principle is demanding since here, the toroidal plasma current needs to be sustained by means of non-inductive current-drive [1]. Although external current drive sources are available, their extensive use would yield an unacceptably high recirculated power fraction in future fusion power plants. Thus, high fractions of the intrinsic bootstrap current are needed which can be maximized in presence of low central poloidal fields, i.e. off-axis current distributions. One way to tailor the current distribution is to use neutral beam injection (NBI) with an off-axis and tangential geometry. Previous studies of the related off-axis NBI current drive efficiency at ASDEX Upgrade during standard H-mode conditions yielded good (neo-classical) fast-ion confinement and current-drive [2]. In presence of low collisionalities, however, the fast-ion slowing down time becomes long such that the relative impact of MHD-induced transport, turbulent transport, charge exchange losses [3] or fast-ion transport due to externally applied error-fields might become stronger. Thus, the fast-ion confinement might be degraded during low-collisionality plasmas which require detailed investigations.

A first step to address the impact of the various redistribution mechanisms is to compare experimental findings with neo-classical theory. Possible deviations of experimental data from the theoretical expectation can then be attributed to so called anomalous transport and analyzed in more detail. One of the most prominent neo-classical fast-ion modeling codes is NUBEAM [4] which is a module implemented in TRANSP [5]. NUBEAM predicts neo-classical fast-ion distribution functions and, combined with TRANSP, yields quantities that can be compared with experimentally accessible data. While the global fast-ion confinement can be addressed by neutron rate measurements, measurements of the plasma stored energy and by neutral particle analyzers (NPA), profile information is obtained from fast-ion D-alpha (FIDA) measurements. Moreover, information on the current profile is obtained from comparisons with the measured loop voltage and with polarization angles from the motional stark effect diagnostic.

Experiments have been performed at ASDEX Upgrade and TCV to address the off-axis fast-ion confinement under various conditions. While ASDEX Upgrade has major and minor radii of 1.65 m and 0.5 m, TCV features major and minor radii of 0.8 m and 0.2 m. ASDEX Upgrade is usually operated at toroidal magnetic field strength of 2.5 T and a plasma current of 1 MA and TCV plasmas are run at 1.45 T and 0.3 MA. In addition, both experiments

are equipped with a flexible and powerful electron cyclotron resonance heating (ECRH) system and NBI. At ASDEX Upgrade eight NBI sources with each 2.5 MW are available of which two sources with 93 keV have and tangential off-axis geometry. TCV has one 25 keV NBI source with 1 MW of power which can be used in an off-axis configuration by shifting the plasma vertically up or down. By comparing the experimental results from both devices with TRANSP modeling, the fast-ion confinement can be analyzed from different perspectives.
This paper is structured as follows. First, experiments at ASDEX Upgrade are discussed during which Alfvén eigenmode activity has been observed and which exhibit strong charge exchange losses as well as strong RMP induced losses. Section 3 then presents experiments at TCV with off-axis fast-ion distribution functions that exhibit strong charge-exchange losses but also drive Alfvén eigenmodes unstable. Finally, a short summary and discussion are given in section 4.

2. OFF-AXIS NBI EXPERIMENTS AT ASDEX UPGRADE

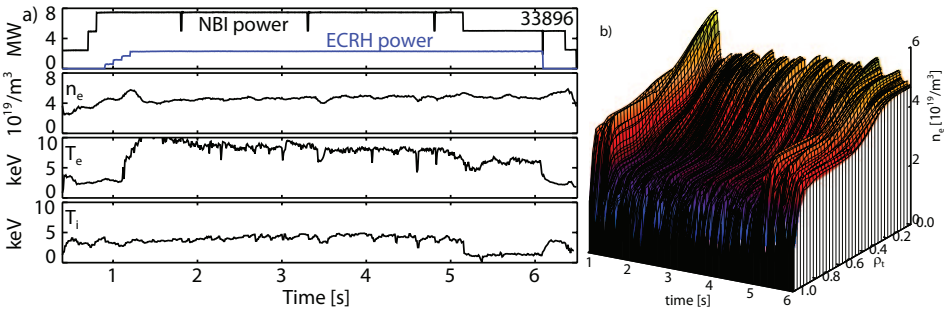

FIG. 1. a) Representative time traces of discharge in #33896 showing the applied heating power, the core electron density and the core electron and ion temperatures. b) Electron density as a function of time and normalized radius.

Time traces of a representative discharge with a central toroidal field of -2.49 T and a plasma current of 600 kA (q95 = 7.5) are shown in figure 1. NBI heating starts early at 0.35 s using the on-axis source NBI Q3, required for charge exchange recombination spectroscopy (CXRS), motional Stark effect (MSE) and fast-ion D-alpha (FIDA) measurements. Early NBI heating reduces the plasma resistivity during the current ramp such that the induced current cannot quickly penetrate into the plasma center and, thus, avoids centrally peaked current profiles. To further increase the off-axis current character of the discharge, two off-axis sources (NBI Q7 and NBI Q6) are turned on at 0.7 s and 0.8 s. Finally, counter-current ECCD is applied in the plasma center from four gyrotrons between 0.9 s and 1.2 s, with a total heating power of 2.3 MW. To lower the collisionality RMPs (n=2) are applied between 1.5s and 5.0s. The density pump-out imposed by the RMPs can be clearly seen in figure 1b.

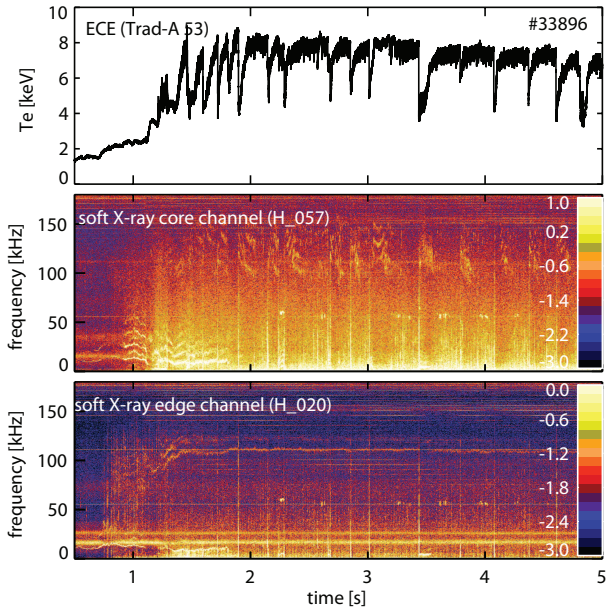

FIG. 2. Temperature in the strong gradient region, measured by the ECE diagnostic, magnetic spectrogram from an soft X-ray channel crossing the core and a channel intersecting the edge region, only.

As consequence of the application of counter-current ECCD and off-axis co-NBI, a current hole develops in the plasma center [6] that is associated with a strong shear region and a transport barrier visible in the electron and ion temperature. Central electron temperatures of up to 10 keV and ion temperatures in the range of 4 keV are observed. When looking at the evolution of the electron temperature in the strong gradient region (see figure 2), sawtooth-like crashes become visible. These crashes are followed by reversed shear Alfvén eigenmodes (RSAEs), as visible in spectrogram of a central soft X-ray channel (see figure 2 middle row). At the plasma edge, toroidicity-induced Alfvén eigenmodes are present that have been detected in an edge channel of the soft X-ray diagnostic. TRANSP modeling has been performed to assess whether the applied perturbations or MHD modes

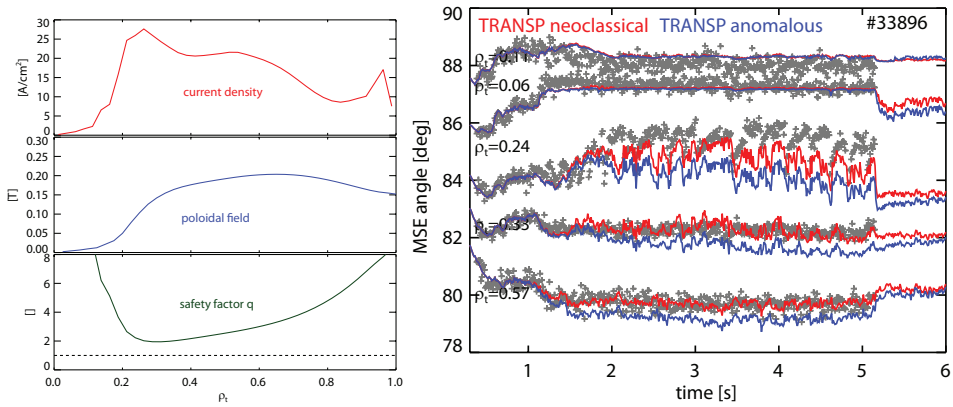

FIG. 3. a) Current, poloidal field and q-profiles as predicted by TRANSP. b) Measured MSE angles compared with TRANSP predictions.

have an impact on the fast-ion distribution function or not. The TRANSP predicted current profile is plotted in figure 3 together with the poloidal magnetic field and the q-profile. The current is close to zero in the plasma center which yields a very low poloidal field and thus high values of the q-profile. To avoid numerical instabilities, the maximum q-value in TRANSP has been limited to q0=8. Despite the application of counter-current ECCD, the discharge is almost non-inductive since the bootstrap current fraction reaches up to 62%, explained by the low poloidal field and the observed high electron and ion temperatures. The predicted evolution of the current profile from TRANSP agrees well with MSE measurements, shown in figure 3b for five radially distributed channels. When instead assuming the ad-hoc anomalous fast-ion diffusion profile, as plotted in figure 4a, the agreement between the measurement and the simulation (blue) becomes worse in figure 3b. The ad-hoc anomalous diffusion

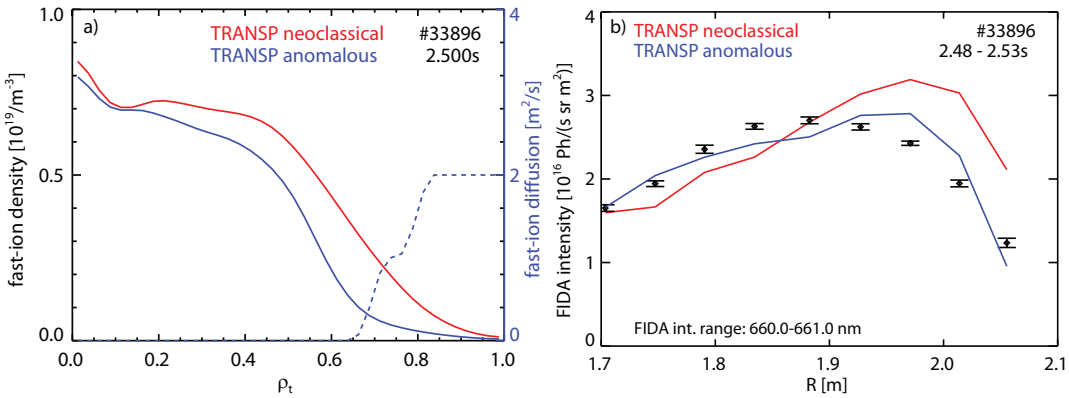

FIG. 4. Radial fast-ion density profiles from TRANSP compared with the applied profiles of anomalous diffusion. b) Radial FIDA profiles compared with TRANSP/FIDASIM results.

profile is, however, needed to explain the radial profiles of the FIDA diagnostic, as shown in figure 4b, which correspond to co-rotating fast ions above 30 keV. When comparing the measured profiles with synthetic profiles from FIDASIM [7], a clear difference is observed close to the plasma edge for the neoclassical fast-ion distribution function (red). Instead, the assumption of anomalous fast-ion transport (blue) yields better agreement, which, however, disagrees with the MSE measurement. Possibly, a velocity space dependent transport is present here which is strong for the bulk fast-ion distribution function (observed by FIDA) but does not affect the high energetic fast-ions which drive most of the plasma current (MSE). In fact, modeling results of the RMP-induced fast-ion transport using LOCUST [8], which are based on perturbed 3D equilibria from VMEC [9], show a dominant redistribution of low-energetic fast-ions. The predicted effect on the FIDA profiles gives the right trend and amplitude. However, LOCUST does not simulate charge exchange losses such that a direct comparison between the fast-ion distribution function from LOCUST and the FIDA or MSE profiles would be misleading. Figure 5a displays the distribution of the applied heating power into heating, charge-exchange losses, shine-though and orbit losses. The charge exchange losses are about 13% of the total injected power. Their level increases during the RMP phase since the fast-ion slowing down time is enhanced. This increase is also observed by a passive NPA diagnostic (see figure 5b) and shows that the predicted enhancement of charge-exchange-losses by TRANSP is correct.

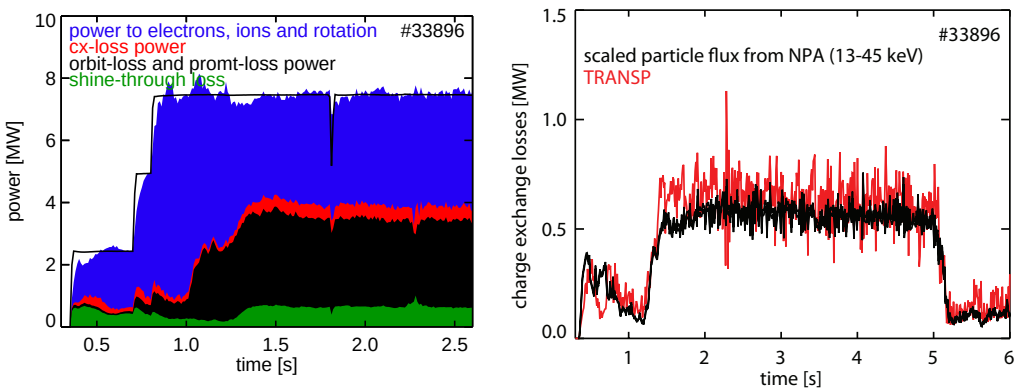

FIG. 5. a) Predicted distribution of the injected NBI power into heating, charge-exchange losses, shine-though and orbit losses. b) Level of charge-exchange losses as a function of time predicted by TRANSP and compared to the relative level of a passive NPA measurement.

The charge exchange losses have been found to be significant in this discharge scenario. The reduced edge-collisionality in presence of the RMP-induced density pump-out yields long fast-ion slowing down times such that charge exchange losses have more time to affect the fast-ion distribution function. In the TRANSP simulation presented here, charge-exchange losses reduce the NBI heating power by up to 0.6 MW (compared with 7.5 MW of NBI heating) and dominantly affect low-energetic fast ions due to the energy-dependence of the charge-exchange cross-section. However, it should be noted that the uncertainty of this prediction is large since the 1D neutral module FRANTIC is applied in TRANSP which does not cover the 3D dependence of the neutral density. The actual level of losses might, thus, be even higher and can, combined with the effect of the RMPs (as predicted by LOCUST), fully explain the observed discrepancies between the neo-classical modelling and the experimental data.

The various MHD modes present in the discharge might redistribute fast-ions but the global fast-ion confinement is affected by charge exchange and RMPs. Moreover, it should be noted that the core localized MHD activity (sawteeth and RSAEs) appear in bursts which would, if a strong transport was involved, result in a temporal variation of the fast-ion density. Such variation is, however, not observed.

3. OFF-AXIS NBI EXPERIMENTS AT TCV

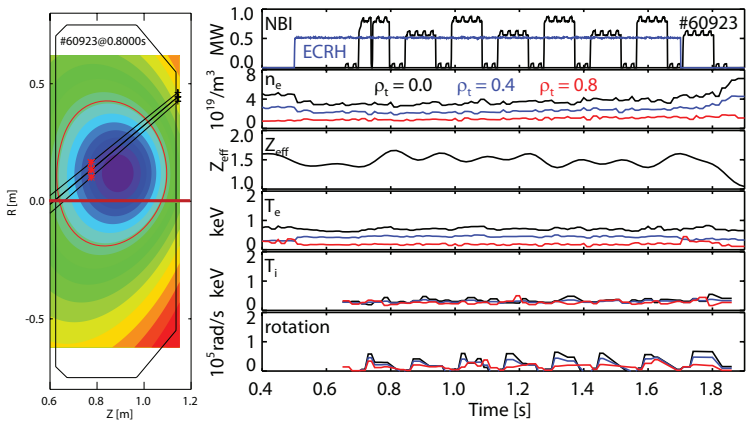

FIG. 6. a) Poloidal cross section of TCV with the plasma shifted vertically upwards by 12 cm such that the neutral beam, plotted in blue, injects off-axis. b) Representative time-traces of discharge #60923.

Experiments have been conducted at TCV with upwards shifted limiter plasmas for an off-axis NBI configuration. As shown in figure 6a, the plasma center was shifted upwards by 12 cm and the ECRH launchers have been adjusted accordingly. The experiment was performed with a plasma current of 120 kA and a reduced magnetic field strength of only 1.3 T during which the 89 GHz gyrotron deposits the power off-axis. The reduced magnetic field was chosen to obtain Alfvén velocities that are below three times the velocity of the fast ions from NBI such

that Alfvén eigenmodes might be excited. Time traces of the experiment are given in figure 6b. The experiment was heated by 0.5 MW of ECRH and the neutral beam was applied with several 96 ms long beam phases. Every second beam phase was performed with a slightly reduced NBI injection voltage (22 keV) to modify the ratio of the fast-ion velocity to the Alfvén velocity. This, however, imposes a reduction of the injected NBI power (see figure 6b). On top of the displayed NBI power from the heating beam, the injected power from the diagnostic beam is plotted, which is, however, hardly absorbed by the plasma due to its high acceleration voltage (50 keV), resulting in significant shine-through. The electron density in the core reaches up to $4 \times 10^{19}/m^3$ and a core electron temperatures of about 1 keV are reached. The ion temperature and plasma rotation are measured by the CXRS diagnostic and clearly respond to the NBI heating phases.

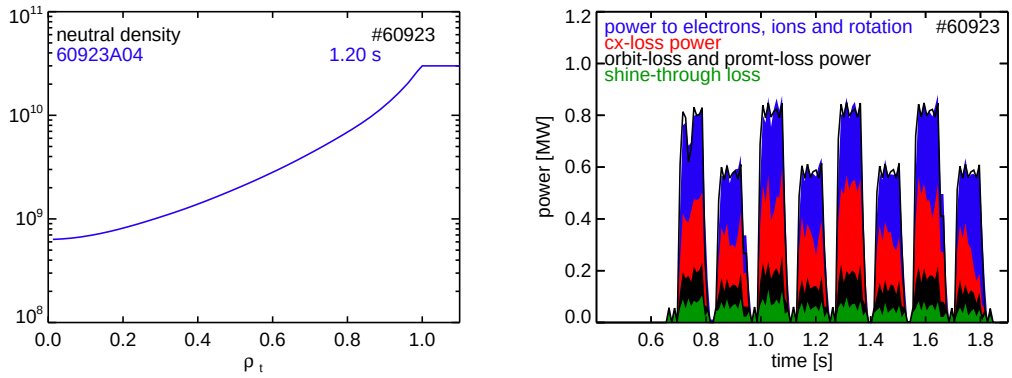

FIG. 7. a) Predicted neutral density profile from TRANSP/FRANTIC. b) Distribution of the injected NBI power into heating, rotation and losses.

TRANSP simulations have been performed for TCV during which the particle confinement time, needed by FRANTIC (see [3]), was modified such that the predicted edge-neutral density matches the data from a baratron at TCV. Figure 7a shows a representative neutral density profile from FRANTIC, which is used in NUBEAM to calculate the level of charge-exchange losses. The high neutral density at the edge, in combination with an off-axis NBI population yields strong charge-exchange losses. Figure 7b illustrates the distribution of the injected NBI power into different channels. As can be seen about 0.2 MW of the injected 0.8 MW of power are lost by charge exchange (25%). The TRANSP simulation with this level of losses agrees well with measurements of the

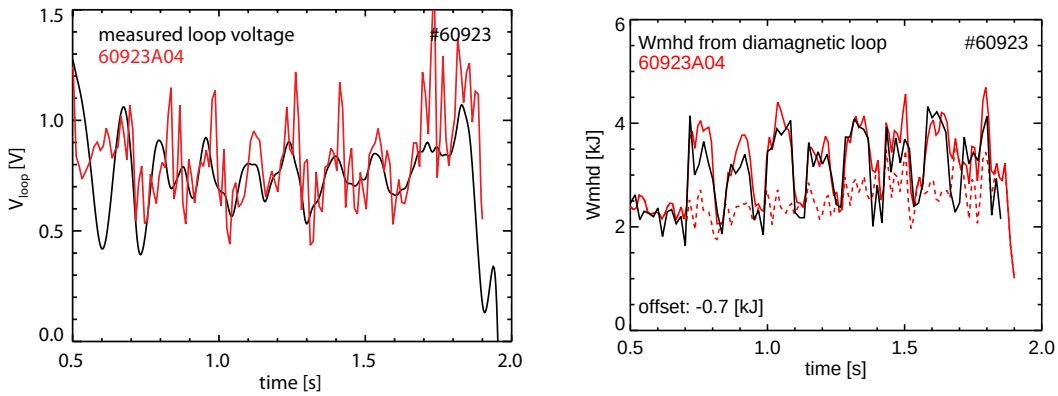

FIG. 8. a) Measured loop voltage compared with the predicted on from TRANSP. b) Measured plasma stored energy compared with the TRANSP prediction.

loop voltage and the plasma stored energy. In figure 8a, the NBI-induced variation of the loop voltage (black) is well recovered by TRANSP (red). In addition, the rise of the plasma stored energy in figure 8b during NBI phase is well matched. The solid red lines represent the TRANSP predicted stored energy including the fast-ion contribution while the dashed lines correspond to the calculated stored energy without fast-ions. This shows that the increase of the stored energy mainly caused by the injected fast-ions. As can be seen in figure 9a, modes appear during each NBI phase at about 80 kHz. The modes have an n=0 component and their frequency might be explained by an Energetic-Particle-Induced Geodesic Acoustic Mode (EGAM) at the q=2 rational surface. During comparison experiments with an on-axis NBI configurations, the modes did not appear, likely explained by

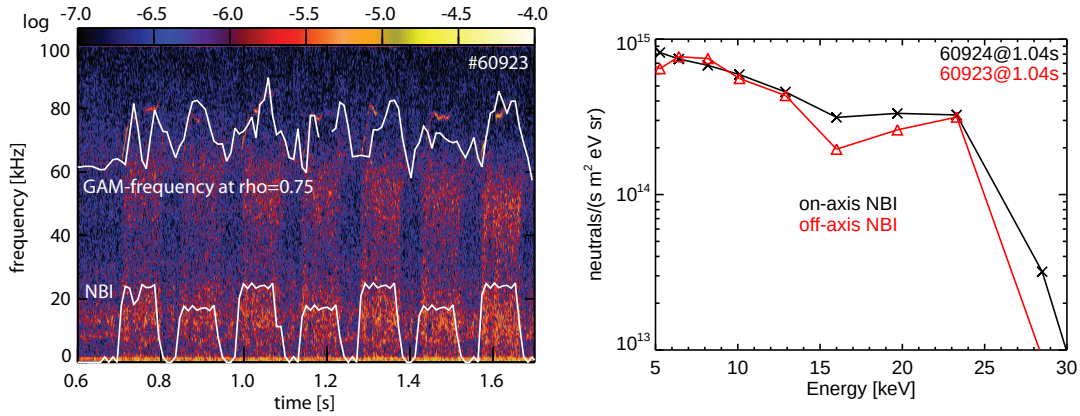

FIG. 9. a) Magnetic spectrogram during discharge #60923 at TCV, featuring NBI-induced Alfvén eigenmode activity. b) NPA measurement during off-axis NBI compared with a similar discharge during on-axis NBI.

different gradients in the fast-ion velocity distribution function. As an example, figure 9b shows energy spectra from the NPA diagnostic during on-axis and off-axis NBI. The shape of the off-axis NBI distribution function is inverted since the injected fast ions do not slow down but rather get lost by charge-exchange reactions. The resulting bump-on-tail distribution function is well know to drive EGAMs. During on-axis NBI, in contrast, the shape of the energy spectrum is flat and explains the absence of EGAMs.

4. SUMMARY AND DISCUSSION

The fast-ion confinement has been investigated in experiments with off-axis NBI at TCV and ASDEX Upgrade which both feature low collisionalities and Alfvén eigenmode activity. The fast-ion confinement in both experiments is clearly affected by charge exchange losses which can easily interact with the off-axis fast-ion distribution function since the density of neutrals from the walls decays exponentially towards the plasma center. From the analysis of ASDEX Upgrade data, strong transport of rather low energetic fast-ions is required. Charge exchange losses fulfill this condition since the charge exchange cross-section peaks at low energies. During the application of RMPs, the level of charge-exchange losses becomes particularly strong since the associated density-pump-out prolongs the fast-ion slowing down time such that the relative impact of charge-exchange losses increases. At TCV, charge exchange losses are strong since the neutral beam has only 25 keV and since the minor radius is small (0.2 m) such that neutrals can easily reach half radius. In contrast, the impact of Alfvén eigenmode activity on the fast ions is not clear in either devices. It is of course clear from other experiments with e.g. FILD detectors that Alfvén modes can give rise to losses. However, a clear impact on the global fast-ion confinement as e.g. observed at DIII-D [10] is has not yet been observed. This is likely explained by the lack of many modes.

ACKNOWLEDGMENTS

This work was partly performed 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. Furthermore, funding from the EUROfusion Enabling Research work-package AWP15-ENR-09/IPP-02 is acknowledged. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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