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A neutron camera system for MAST[a)]

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A prototype neutron camera has been developed and installed at MAST as part of a feasibility study for a multichord neutron camera system with the aim to measure the spatial and time resolved 2.45 MeV neutron emissivity profile. Liquid scintillators coupled to a fast digitizer are used for neutron/gamma ray digital pulse shape discrimination. The preliminary results obtained clearly show the capability of this diagnostic to measure neutron emissivity profiles with sufficient time resolution to study the effect of fast ion loss and redistribution due to magnetohydrodynamic activity. A minimum time resolution of 2 ms has been achieved with a modest 1.5 MW of neutral beam injection heating with a measured neutron count rate of a few 100 kHz.

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I. INTRODUCTION

The Mega Amp Spherical Tokamak (MAST) is a medium sized spherical tokamak (ST) with a poloidal cross-section and plasma current comparable to medium sized conventional tokamaks such as DIII-D and ASDEX-U. Additional heating is primarily provided by a high power neutral beam injection (NBI) system ($\leq$3.8 MW to date). MAST's scientific program is devoted to exploring the potential of the ST concept as prospective fusion materials and components test facility and/or a power plant, and to address key physics issues for ITER such as the characterization and impact of edge localized modes, neoclassical tearing modes, as well as access to and properties of high confinement regimes. In particular, the study of fast particle driven collective instabilities, such as Alfvén eigenmodes (AE), and the effect of fast particles upon core instabilities are of major interest. Due to the relatively low toroidal field, the fast ions injected by the NBI system, with energies around 60 keV, have velocities above the Alfvén velocity and can therefore excite Alfvén instabilities. These conditions are similar to those that are expected in ITER where a super-Alfvénic alpha particle population will be created: MAST therefore constitutes an ideal test bed to study the interplay between fast ions and AEs in different advanced tokamak scenarios. Collective instabilities affect the fast ion energy distribution and their confinement properties leading to their redistribution and loss thereby affecting the neutron emissivity profile. It is therefore vital for the understanding of these processes to measure the fast ion distribution with good time and spatial resolution. In addition, a time resolved measurement of the neutron emissivity profile provides additional constraints for transport codes such as TRANSP. The NBI injected fast ions undergo $D(d,n)^3$He fusion with the thermal ion population with the emission of 2.45 MeV neutrons. These beam-thermal neutrons, in combination with a smaller percentage of beam-beam neutrons ($\approx$20% in MAST), thereby provide a direct indication of the time and spatial evolution of the fast ion distribution. In MAST, the total neutron source strength is measured with an absolutely calibrated 1.34 g ^{235}U fission chamber (FC) located in close proximity to the vessel with a time resolution of 10 μs. A conceptual study of a multichord neutron camera capable of measuring the neutron emissivity along collimated lines of sight[1] has lead to the design and construction of a prototype neutron camera (NC) that has now been installed on MAST. The prototype NC is presented in Sec. II, while the first experimental results and conclusions are discussed in Secs. III and IV respectively.

II. THE PROTOTYPE NEUTRON CAMERA

The conceptual study for the multichord NC was carried out on the basis of expected neutron emissivity profiles, obtained from TRANSP simulations, in relevant plasma scenarios for fast ion studies (where AE activity is ubiquitous). The poloidal neutron emissivity profiles obtained by TRANSP simulations, an example of which is shown in Fig. 1, were used in MCNP, together with a model of the MAST machine and surrounding structures, to calculate the expected neutron field at the candidate NC location. The information provided by both TRANSP and MCNP was then used for the final design of the prototype NC also taking into account constraints in the MAST area both in terms of physical space and electromagnetic noise.

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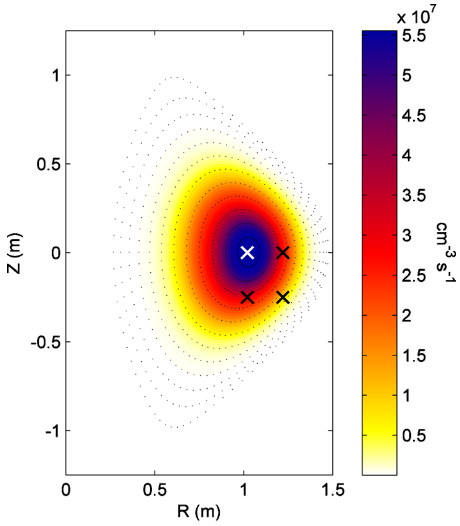

FIG. 1. (Color online) TRANSP neutron emissivity profile: The crosses indicate the intersection of the LoS with the major radius for the equatorial (top row) and diagonal (bottom row) fans.

A. Geometry of the lines of sight

The NC has an equatorial and a vertically inclined ("diagonal") fan of two lines-of-sight (LoS) each. Since the NC is installed on a rail, all four LoS have a variable impact parameter (normal intersection of the LoS with the major radius) to measure the neutron emissivity profile (by exploiting shot-to-shot repeatability). The equatorial fan has its LoS lying in the MAST equatorial plane, as defined by the vacuum vessel geometry, viewing the plasma through a very thin stainless steel flange (3 mm thick) to avoid strong attenuation of the neutron flux. The diagonal fan LoS has the same impact parameter of the equatorial views but is inclined so as to intersect the major radius 25 cm below the equatorial plane (see Fig. 1). The diagonal fan was specially designed for off-axis NBI heating scenarios.

The spatial separation of the normal intersection with the major radius of the two LoS in each fan is 20 cm, corresponding to a difference in the neutron emissivity profile of approximately 50% and roughly to the spatial scale of the location of the projected copassing orbits of the fast ions. The collimators of all four LoS are 90 cm long with a rectangular cross-section with the short side (2 cm) parallel to the equatorial plane and with the long side (5 cm) parallel to the machine axis (MAST plasmas being characterized by high elongation $\kappa \approx 2$ and correspondingly elongated fast ion orbits). The LoS geometry is shown in Fig. 2.

B. Shielding

The detectors are protected from background radiation by a 90 cm thick shielding made out of slabs of high density pure polyethylene, interlocked with each other to reduce neutron streaming between gaps. To reduce the overall weight of the neutron shielding its thickness at the rear is only ≈40 cm as fewer scattered neutrons are predicted to reach the detectors from behind. The optimal thickness of the neutron shielding was determined via MCNP simulations of the direct neutron spectrum at the detector location. Additional MCNP calculations were then carried out to calculate the line integrated "direct," "indirect," (having scattered on MAST vessel into the LoS) and scattered neutron flux. The results obtained clearly indicate that the indirect neutron flux contribute a factor 10 less to the total flux compared with the direct neutrons except at the plasma edge. The polyethylene shielding is a source of 2.23 MeV γ rays against which the detectors are protected by a close fitting lead shield of approximately 10 cm thickness. In between the polyethylene and lead shields, two soft iron boxes each 1 cm thick protect the detectors from MAST's stray magnetic fields. These together with a 0.5 mm inner layer of μ-metal reduce the overall stray magnetic field at the detectors' location during a MAST pulse to less than 0.15 mT.

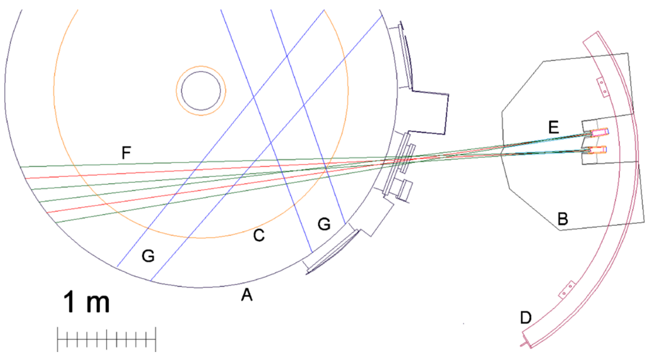

FIG. 2. (Color online) Top view of MAST equatorial plane and of the prototype NC (right). (a) Vessel, (b) neutron shielding, (c) plasma boundaries, (d) rail, (e) lines of sight, (f) fields of view, and (g) NBI beams.

C. Detectors and data acquisition system

Each of the four liquid scintillator (EJ-301) detectors has an active volume of 10 cm^3 (2 cm wide, 5 cm tall). The thickness of the active volume was chosen to be much larger than the range of 2.45 MeV protons in the material. The scintillator is coupled to a Hamamatsu R5611 photomultiplier tube (PMT) via a short BK7 glass lightguide which can be illuminated by a blue light-emitting diode (LED). The LED system is used for monitoring the PMT gain stability at high count rates. Each PMT is protected from stray magnetic fields by an additional 0.8 mm μ-metal shield. On the side of the detector (not facing the plasma) a ^{22}Na γ source is mounted and is used, together with the LED system, for monitoring and calibration purposes. Each detector is equipped with a temperature sensor and a common water-cooled heat exchanger connected to all the detectors by copper braids. Laboratory tests indicated a maximum temperature increase of approximately 5 °C per detector. Signals are sent, via 5 m long RG58 cables, to a 14 bit, 250 MHz sampling frequency, dual channel transient recorder (Spectrum M3i.4121) with 256 MS onboard memory with multitrigger and time-stamp functionalities. Data acquisition can be continuous or triggered by individual pulses in which case a corresponding time-stamp is generated. Pulse shaped discrimination (PSD) is used to identify gamma ray, neutron and LED events from which the neutron count rate and pulse height spectra are obtained.

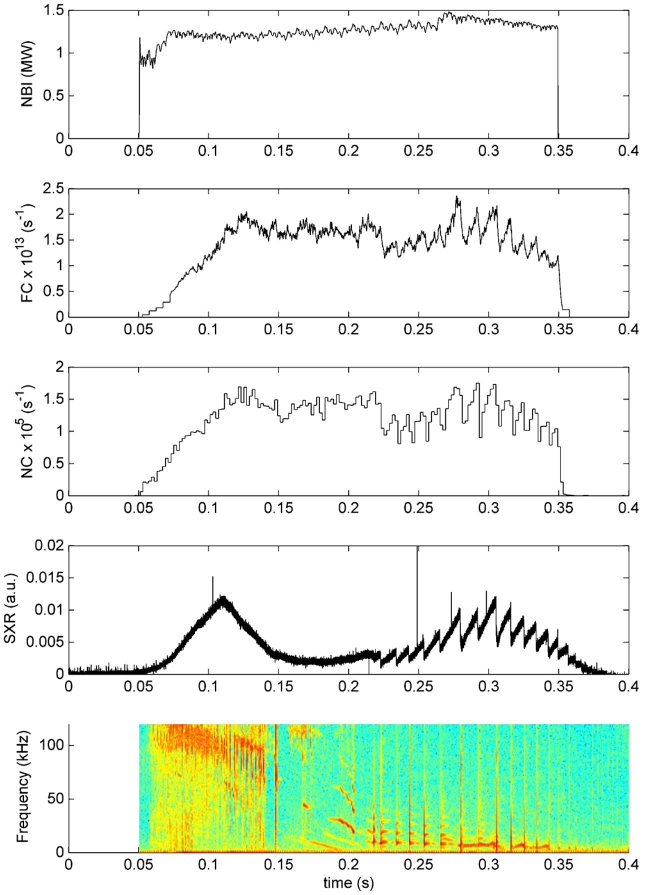

FIG. 3. (Color online) Pulse no. 25004: NBI power, FC neutron yield, NC neutron count rate, soft X-rays, and Mirnov coil spectrogram.

III. FIRST EXPERIMENTAL RESULTS

At present only the equatorial fan is installed. First results have been obtained in plasma scenarios relevant for fast ion and H-modes studies with 1.2–3.2 MW of NBI heating, 0.3–0.8 MA plasma currents, $0.1-1.0\times 10^{20}$ m^{-3} electron densities, and $0.1-1.4\times 10^{14}$ s^{-1} neutron rates (measured with the FC). The NC total count rate per detector is in the range of $0.3-1\times 10^{6}$ s^{-1} with neutron count rate in the range of $2-6\times 10^{5}$ s^{-1}. Figure 3 shows the time evolution, with a 2 ms time resolution for MAST discharge no. 25004, of the NC count rate together with the FC neutron yield, and total NBI power. The simultaneous crashes in neutron yield seen by the NC and the FC are associated with strong sawtooth activity as the bottom two panels of Fig. 3 clearly show. A comparison between the two LoS of the equatorial fan for discharge no. 25087 is shown in Fig. 4: The difference in neutron count rate (top panel) is a consequence of different plasma regions seen by the two LoS. For this plasma pulse a neutron yield of 1.4×10^{14} s^{-1} was measured by the FC resulting in a NC neutron count rate of 5.5×10^{5} s^{-1} while the total count rate exceeded 1 MHz. At these high count rates changes in the PMT gain stability are to be expected. The uncalibrated neutron PHS for the two LoS (shown in the bottom panel of Fig. 4) has been calculated in the time interval of 0.28–0.32 s where the count rate was constant. The differences in the PHS for the two LoS are probably due to: (a) the different relative angle between each LoS and the injected NB; (b) the different plasma regions probed by the two LoS. A detailed study of the PHSs will be carried out in a future work by modeling the neutron source using TRANSP convolved with the detectors' response function.

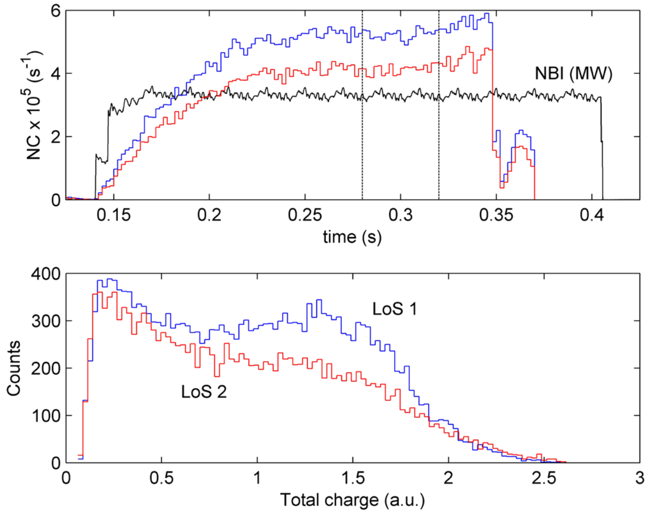

FIG. 4. (Color online) Pulse no. 25087: NC neutron count rate for two LoS with NBI power (black) and the time interval (dashed lines in the top panel) integrated, uncalibrated neutron PHS.

IV. CONCLUSIONS

A prototype NC has been installed at MAST and the preliminary results obtained so far confirm its capability to measure neutron emissivity profiles with enough time resolution (below 2 ms) to study the effect of fast ion loss and redistribution due to magnetohydrodynamic activity already at 1.5 MW of NBI input power.

ACKNOWLEDGMENTS

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[1] M. Cecconello, S. Conroy, G. Ericsson, M. Weiszflog, R. Akers, and M. Tumyanskiy, Proceedings of the Fourth IAEA Technical Meeting on Spherical Tori and 14th International Workshop on Spherical Torus, ENEA, Frascati, Roma, Italy, 7–10 October 2008.