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Conceptual design of a neutron camera for MAST Upgrade[a)]

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This paper presents two different conceptual designs of neutron cameras for Mega Ampere Spherical Tokamak (MAST) Upgrade. The first one consists of two horizontal cameras, one equatorial and one vertically down-shifted by 65 cm. The second design, viewing the plasma in a poloidal section, also consists of two cameras, one radial and the other one with a diagonal view. Design parameters for the different cameras were selected on the basis of neutron transport calculations and on a set of target measurement requirements taking into account the predicted neutron emissivities in the different MAST Upgrade operating scenarios. Based on a comparison of the cameras' profile resolving power, the horizontal cameras are suggested as the best option. © *2014 AIP Publishing LLC*.
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I. INTRODUCTION

On the Mega Ampere Spherical Tokamak (MAST),[1] fusion reactions between fast ions, from auxiliary heating by Neutral Beam Injection (NBI), and thermal ions in the plasma account for approximately 90% of the neutron emission. For this reason, the observation of the spatial distribution of the neutron emission with a neutron camera allows to study the fast ion confinement. This confinement can be reduced by magneto-hydro-dynamic (MHD) instabilities, as recently studied on MAST using a suite of fast ion diagnostics, including a proof-of-principle neutron camera.[2] Based on the encouraging results obtained by this system and in view of the MAST Upgrade project,[3] conceptual studies have been carried out to explore different design solutions for an upgrade of the proof-of-principle to a full neutron camera with multiple lines of sight enabling profile measurements of the neutron emissivity in a single plasma discharge.

II. NEUTRON EMISSION IN MAST UPGRADE

MAST is a medium sized spherical tokamak, currently undergoing a major upgrade that will extend its operating regimes by, among other things, an increase in the NBI heating power from today's 5 MW to 7.5 MW and, at a later stage, possibly up to 10 MW.[3] The injection of fast ions will take place over a wider plasma region, which will be achieved, in the first stage of MAST Upgrade, by two NBIs injecting the beam ions in tangential direction, one in the equatorial plane (on-axis NBI) and one 65 cm above it (off-axis NBI). For the different MAST Upgrade scenarios, the expected neutron rates will be in the range 10^{14}–10^{15} n/s, a factor 10 up from present MAST plasma discharges, and the beam-thermal component will still be dominant, that is, the neutron emission will be a good proxy of the fast ion population spatial distribution.

III. NEUTRON CAMERA UPGRADE

The following design criteria have been set for the neutron camera upgrade: (1) Operation compatible with neutron rates between 10^{14}–10^{15} n/s; (2) time resolution of 1 ms with a statistical uncertainty of not more than 10% on the counts from the plasma core; (3) spatial resolution of 6–8 cm with full coverage of the plasma poloidal cross section and a radial overlap (full penumbra footprint) between neighboring sight lines of 50%. The detection system consists of liquid scintillator detectors coupled to PM tubes. Based on the experience from the prototype neutron camera, High Density PolyEthelene (HDPE) is chosen for neutron shielding and collimation.

A lead shield around the detectors is required against the γ-ray emission from thermal neutron capture in hydrogen. Shielding is also needed against the higher stray magnetic field, to reach the same field at the detector position as in the proof-of-principle neutron camera and the same disturbance of the plasma equilibrium field, not exceeding a value of 0.3 mT for distances smaller than 2 m from the central solenoid. Based on these design criteria, two different neutron camera systems have been studied: the first one consisting of two horizontal cameras, one equatorial and one vertically down-shifted by 65 cm, and the second one, viewing the plasma in a poloidal section, also consisting of two cameras, one radial and the other with a diagonal view.

A. Neutron transport calculations

The camera designs have been evaluated with the neutron transport code MCNP.[4] A model of the major components of MAST Upgrade (concrete walls, vacuum vessel, magnetic field coils) was coupled to a model of the respective camera.

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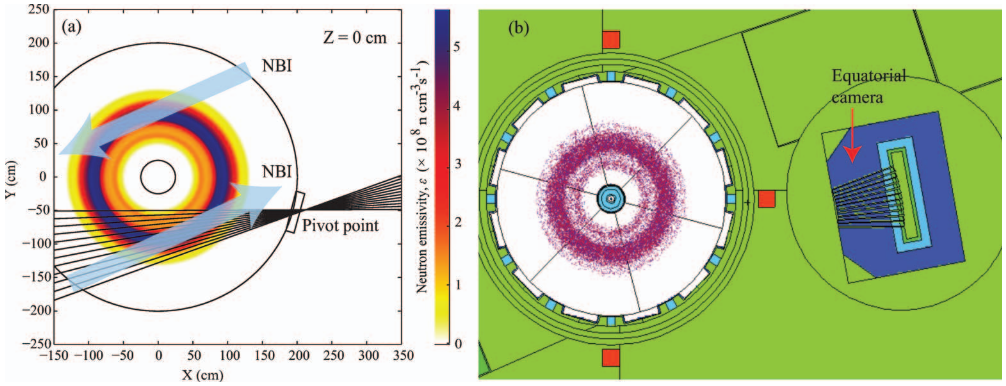

FIG. 1. Equatorial neutron camera. (a) Sight lines and indicative NBI beams. (b) MCNP model with MAST Upgrade vacuum vessel and neutron camera.

The neutron source model was derived from TRANSP simulations for MAST Upgrade plasma scenarios. The equatorial on-axis camera was designed as follows: The requirement on the spatial resolution leads to 12 sight lines, giving a spatial resolution of about 6.4 cm. The detectors' location and the required magnetic shielding were determined on the basis of the stray magnetic field at the detector position and the perturbation it caused to the plasma equilibrium field: Electromagnetic field calculations indicate a distance of 5 m from the central solenoid and magnetic shielding consisting of 4.8 cm soft iron and 2 mm μ-metal as the optimal design. MCNP calculations indicate that a 15 cm thick layer of lead surrounding the detectors and their magnetic shielding is required in order to attenuate the γ-ray flux on the detectors to about 10% of the neutron flux even for non-core sight lines. Both the γ-ray and the magnetic shielding also serve as parts of the neutron collimator. The thickness of the HDPE neutron shielding was calculated on the basis of the ratio between direct and scattered neutrons and between neutrons and γ-rays. The obtained neutron shielding thickness of 95 cm leads to an overall collimator length of 115 cm. The sight lines, the intersection with the plasma and the MCNP model of the equatorial on-axis neutron camera are displayed in Figure 1. Figure 2 shows the composition of the detector shielding against neutrons, gammas and the magnetic field.

The neutron, γ-ray, and magnetic field shielding so obtained was kept constant for all camera design options while collimator radius and detector thickness were adjusted to meet the required overlap and detection efficiency. For the equatorial neutron camera, cylindrical collimators of 1 cm radius were selected and the detectors' efficiency had to be 11%, corresponding to a 25 mm thick liquid scintillator. The poloidal section camera, discussed in detail in Ref. 5, consists of a radial camera with 12 sight lines and diagonal camera with 9 sight lines, see Figure 3. Note that, due to interfacing constraints at MAST Upgrade, a design with a radial and a vertical camera, as installed, e.g., at JET,[6] can not be realized here. The relevant parameters for all four neutron cameras are summarized in Table I.

B. Performance analysis

The performance of the different camera designs is judged from their ability to observe *(a)* details and *(b)* changes in the neutron emission profile in all MAST Upgrade scenarios. In order to address issue *a*, the simulated emission profiles, including effects from the finite opening angle of the viewing cones and from scattered neutrons, are compared to line integrals of the neutron emissivity along the sight lines, taking into account only direct neutrons from the central axis of the viewing cone. The good agreement, see Figure 4, indicates that the chosen number of sight lines and overlap maintain all details in the emission profile. The results are similar for all four cameras, slightly better for the equatorial and the radial cameras than for the down-shifted and the diagonal ones, due to the higher proportion of scattered neutrons in the latter two.

Fast particle redistributions often result in changes in the neutron emission along the major radius which can be observed as rigid shifts of the entire profile. In order to compare the different cameras' sensitivity to such shifts, a neutron

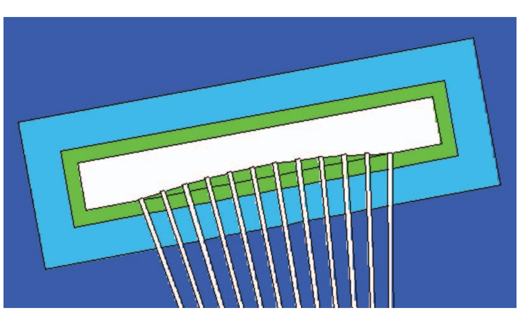

FIG. 2. Inner parts of the neutron camera shielding. Color code: Dark blue: HDPE. Light blue: Lead. Green: Soft iron and μ-metal. White: Air.

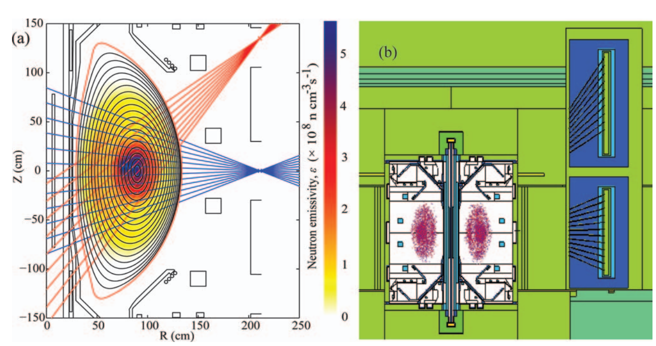

FIG. 3. Poloidal neutron camera. (a) Sight lines for the radial (blue) and the diagonal (red) camera. (b) MCNP model.

TABLE I. Design parameters of the neutron cameras options. The collimator length is 115 cm in all cases.

Camera	Sight lines	Spatial resolution	Collimator radius	Detector thickness
Equatorial	12	6.4 cm	1.00 cm	25 mm
Down-shifted	8	7.2 cm	1.15 cm	40 mm
Radial	12	8.4 cm	1.25 cm	25 mm
Diagonal	9	7.5 cm	2.00 cm	25 mm

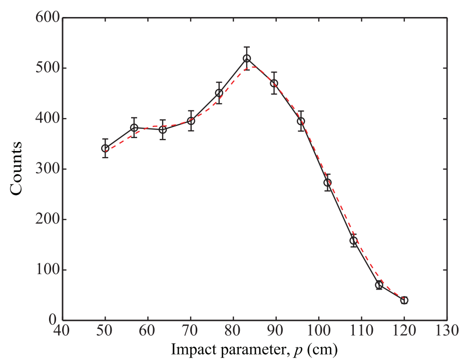

FIG. 4. Simulated neutron profiles (symbols and black line) for the equatorial camera in comparison to line integral calculations (dashed red line). The error bars reflect the statistical uncertainties for a typical expected MAST Upgrade plasma and a measuring time of 1 ms. The impact parameter is the closest distance of the sight line to the tokamak central axis.

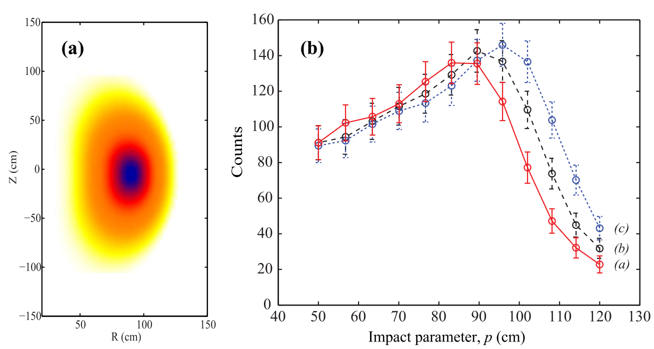

FIG. 5. (a) Neutron emission profile for a MAST reference scenario and (b) the expected measured profile for the equatorial neutron camera for the original emission (a) and shifts by 5 cm (b) and 10 cm (c). The error bars reflect the statistical uncertainties for a measuring time of 1 ms.

TABLE II. Figures of merit for the different neutron camera designs and radial shifts of the plasma. For details see text.

Camera	*FOM* (5 cm)	*FOM* (10 cm)
Equatorial	9.1	32.9
Down-shifted	37.3	50.3
Radial	0.1	0.2
Diagonal	1.2	4.6

emission profile was radially shifted by 5 and 10 cm and the expected count rates were calculated for the different cameras. For the horizontal on-axis camera, the unshifted emission profile and the camera profiles for the original and two radially shifted profiles are shown in Figure 5. The camera's sensitivity can be characterized by a figure of merit, given by

$$FOM = \sum_i \frac{(N_{\text{i, before}} - N_{\text{i, after}})^2}{(\sigma_{\text{i, before}} + \sigma_{\text{i, after}})^2},$$

where N_i is the number of counts in detector i and the summation is performed over all sight lines of the respective camera. A large *FOM* indicates a high sensitivity. The figures of merit for the different camera designs, see Table II, indicate that a combination of an equatorial and a down-shifted camera has a high sensitivity to radial shifts of the neutron emission. Plasma shifts along the z-axis, e.g., caused by off-axis NBI heating, could hardly be observed by an equatorial or a down-shifted camera alone, the comparison of the count rates in the two instruments, however, allows the observation of even those shifts. The radial camera does not allow the observation of radial shifts, the diagonal camera is less sensitive than the horizontal ones.

IV. CONCLUSIONS

Preliminary conceptual design options for an upgraded neutron camera for MAST Upgrade have been investigated. Two camera systems, a horizontal one and a poloidal section system, have been compared on the basis of their capability to detect details and changes in the neutron emissivity profile. Based on the obtained results, the horizontal camera system comprising an equatorial and a down-shifted camera is suggested as a strong candidate for installation at MAST Upgrade. The on- and off- axis cameras complement each other well: for most scenarios the on-axis camera has a superior resolving capability compared to the off-axis one apart from a few scenarios with large anomalous fast ion diffusion or off-axis NBI heating where the opposite holds.

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