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A poloidal section neutron camera for MAST Upgrade

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Abstract. The Mega Ampere Spherical Tokamak Upgrade (MAST Upgrade) is intended as a demonstration of the physics viability of the Spherical Tokamak (ST) concept and as a platform for contributing to ITER/DEMO physics. Concerning physics exploitation, MAST Upgrade plasma scenarios can contribute to the ITER Tokamak physics particularly in the field of fast particle behavior and current drive studies. At present, MAST is equipped with a prototype neutron camera (NC). On the basis of the experience and results from previous experimental campaigns using the NC, the conceptual design of a neutron camera upgrade (NC Upgrade) is being developed. As part of the MAST Upgrade, the NC Upgrade is considered a high priority diagnostic since it would allow studies in the field of fast ions and current drive with good temporal and spatial resolution. In this paper, we explore an optional design with the camera array viewing the poloidal section of the plasma from different directions.

Keywords: MAST Upgrade; neutron camera; fusion diagnostic
PACS: 52.70.-m

INTRODUCTION

MAST is a low aspect ratio spherical torus with deuterium neutral beam injection of up to 5 MW and has achieved a typical neutron yield of $\sim 10^{13}$ n/s and a maximum of 2×10^{14} n/s. As a part of MAST Upgrade, the neutral beam power will be increased to 7.5 MW and finally 12 MW [1], resulting in an expected higher neutron emissivity. MAST Upgrade will allow testing of the fast particle behavior in ITER relevant plasma scenarios and studying of the off-axis current drive. At present, a proof-of-principle neutron camera (NC) [2] is in use at MAST. The NC has views the plasma through a limited number of collimated sight lines and is mounted on a movable platform. Due to the limited number of sight lines, data from about 4-6 identical plasma discharges are needed in order to provide an estimate of the plasma emissivity profile. The NC has provided information on the interplay between MHD activities and fast particles [3] and on the effect of off-axis current drive on fast particle redistribution. Based on the results from the NC, a conceptual design for an upgraded NC in the horizontal plane with tangential view was developed [4]. The main focus of the NC Upgrade is to provide information on the neutron emissivity profile in a single plasma discharge and to introduce the possibility of multiple fans of lines of sight. The advantage of the tangential view as used for the existing NC, as well as in [4], is minimizing the back-scattering neutron from the opposite wall.

For a D-shaped cross section devices such as JET and ITER, as well as MAST Upgrade, neutron collimated measurements in both poloidal and vertical plane are required for accurate reconstruction of the neutron emitting region. Poloidal section cameras are used at JET [5] and planned for ITER [6]. Neutron tomography based on the use of radial and vertical cameras is a powerful experimental technique for investigating the dynamics of the spatial distributions of the fast ions in experiments on JET [5].

Here, we explore an optional design of the NC Upgrade with the cameras viewing the poloidal section of the plasma from different directions. The poloidal camera would also suffer from a large component of back-scattered neutron from the poloidal and toroidal field coils, divertor plates, central solenoid, etc. The Monte Carlo code MCNP was used for simulating the performance of different design solutions.

In [4], the detectors envisaged for the NC Upgrade are the scintillators coupled to PMTs due to their high efficiency in mixed n/γ field detection and good n/γ separation as the detectors used for the existing NC as the possibility of neutron spectroscopy. However, PMTs suffer from gain variations due to high count rate, temperature and magnetic field. Thus, PMTs based on silicon-based light detector and several candidate detectors such as fission chambers based on ^{238}U and diamond detectors are considered.

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DESIGN OF THE POLOIDAL SECTION CAMERA

The design of the camera must fulfil the requirements on the measurement of the neutron emissivity at MAST Upgrade of 10 % statistical uncertainty on the number of neutron count rates for each sight line with 1 ms time resolution for the expected neutron emissivities.

The design of the poloidal section camera is adapted to the MAST Upgrade design including massive structures such as upper and lower divertor plates, poloidal and toroidal field coils, port flanges, vacuum, vessel wall, etc. Therefore, the radial and diagonal fan shapes arrays, hereafter referred to as radial and diagonal camera, are proposed while the vertical sight lines are not considered due to the interference of their field-of-view with the existing divertor plates.

The design target for the radial camera is to completely cover the plasma in vertical direction while simultaneously providing good spatial resolution. The detector position should be shielded against neutron and γ radiation, magnetic fields, etc. We propose placing the radial camera in the equatorial plane. An array with twelve sight lines is housed at the equatorial port (figure 1a). The detection neutron fluxes from the plasma center is in the region of -47 cm $< r <$ 47 cm (in the minor radius of the plasma in the vertical direction) with 8.54 cm spatial resolution, covers an angular field of 40.48°. The radial camera contains the cylindrical collimators and detector channels 01-12 (the collimator dimensions will be selected after detailed MCNP calculations).

In order to allow a tomographic analysis, an additional diagonal camera is designed as shown in figure 1a. Nine sight lines viewing tangentially vertical extent of each collimator channel at the vertical minor radius is -27 cm $< r <$ 53 cm, covers an angular field of 13.97°. The camera contains detector channels 13-21. The twenty one detectors (its thickness will be selected after detailed MCNP calculation) are located at the end of the collimator channels recording both neutrons and γ-rays emission data which will be stored as time traces for each plasma discharge.

SIMULATION, RESULTS AND DISCUSSION

The MCNP contains the geometry and material of the designed poloidal section camera and the MAST Upgrade vessel as well as the experimental hall. Other structures, like the neutral beam boxes and other diagnostics, not taken into account are expected to have a very small impact on the simulation results in this work. The neutron source is a non-flux surface averaged neutron emissivity obtained by TRANSP simulations for relevant MAST Upgrade plasma scenarios C [1]. It is represented as a toroidally symmetric neutron emissivity together with a simplified (Gaussian) 2.45 MeV neutron energy spectrum with the full width at half maximum, FWHM $\sim$ 330 keV.

A detailed MCNP model of the poloidal section camera has been developed, consisting of: *i)* the collimator channels of radial and diagonal cameras; *ii)* a high density polyethylene (HDPE) shields; *iii)* lead shields; *iv)* soft-iron shields, one inside the others for each camera. The performed MCNP simulations provide the neutron and γ-ray fluxes at the purposed detector position and shielding. The decision of the collimators length, radii and the detector thickness is based on: *i)* the capability to construct the spatially collimated (line integrated) neutron emissivity profile; *ii)* the adequate collimation neutron fluxes achieving the required statistical uncertainty (10 %) and time (1 ms) resolution in measuring neutrons and *iii)* the sufficient thick shielding to reduce the neutron reaching the detectors and to shield the scattered neutrons and background γ-rays.

Spatial resolution and neutron fluxes

The principle design of the collimators is based on a compromise between the requirements on spatial resolution (little overlap between the fields of view) on the one and on time resolution (sufficiently high count rate) on the other side. Even the interference between the detectors and their shielding and the magnetic field around the MAST tokamak has to be taken into account. Following the magnetic field calculations presented in [4], the detector position is at 500 cm from the central column and the detector are shielded with the 6 cm thick of soft-iron box and 2 mm thick of μ-metal. The computation were performed for different collimator dimensions between 0.75 cm and 1.5 cm for the radial camera collimator radius and between 1 cm and 2.5 cm for diagonal camera collimator radius and between 100 cm and 150 cm for collimator length of both cameras, where the shielding thickness is well defined by the collimator length. In order to achieve good spatial resolution, the collimator should have a long length and a small radius. To achieve the time resolution in measuring neutron, the scintillator detector thickness is varied between 1 cm and 3.5 cm which give the neutron detection efficiency, obtained from MCNP calculations, in range of 5 % to 14 %. The simulated neutron

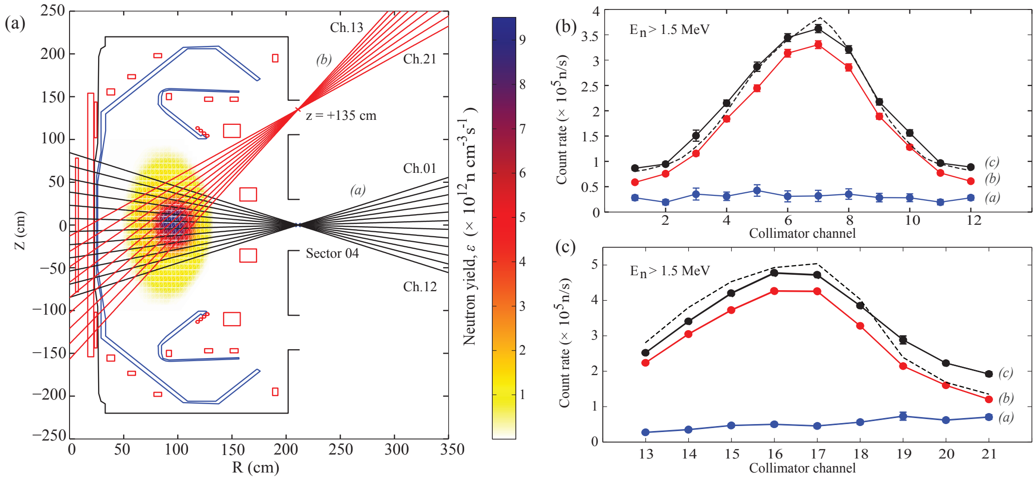

FIGURE 1. (a) the poloidal section view of MAST Upgrade vessel including the position of poloidal field coils, solenoid, divertor plates, port flange. The two fan shapes arrays of radial*(a)* and diagonal*(b)* camera superimposed to poloidal neutron emissivity profile are presented. (b) the scattered*(a)*, uncollided*(b)* and total*(c)* neutron count rates profile (E_n > 1.5 MeV) from the proposed radial camera collimator radius 1.25 cm, length 115 cm, detector position 500 cm, neutron detection efficiency 11 % simulated by MCNP code are compared to the line integrated neutron emissivity profile (dashed line). The line integrated profile are normalized to the total neutron count rates profile. The diagonal camera with proposed collimator radius 2 cm shown in (c). The plasma scenario presents in figure is scenario C.

count rates profiles are compared to the line integrated neutron emissivity profile for the radial camera (figure 1b) and diagonal camera (figure 1c). The level of scattered, uncollided and total neutrons with the given detector thickness are shown in the figure. The figures show the capability to reconstruct the neutron emissivity profile with the radial and diagonal camera compared to the line integrated neutron emissivity profile.

The suggested geometry for the radial camera is collimator length 115 cm, collimator radius 1.25 cm, scintillator detector thickness 2.5 cm (neutron detection efficiency 11 % for E_n > 1.5 MeV). The design results in neutron count rates of ∼ 0.10 MHz and ∼ 0.35 MHz for sight lines viewing the plasma edge and plasma core respectively and neutron energies above 1.5 MeV. The suggested geometry for the diagonal camera is collimator length 115 cm, collimator radius 2 cm, scintillator detector thickness 2.5 cm. The design results in neutron count rates in range of of ∼ 0.25 - 0.50 MHz and neutron energies above 1.5 MeV. The proposed collimator and detectors dimensions are provide the high efficiency for measuring the neutron emissivity in order of ∼ 10^5 n/s but the camera does not allow profile construction on the same level of detail as with the horizontal camera outlined in [4].

Background γ-rays and scattered neutrons

In the present design, the neutron shield consists of a thick layer of HDPE (80 × 191 × 340 cm^3 , ∼ 5 ton, for the radial camera and 80 × 191 × 390 cm^3 , ∼ 6 ton, for the diagonal camera). HDPE emits 2.23 MeV γ-rays after neutron capture, which requires additional γ-rays shielding since the detector, assuming the use of scintillators, is sensitive to both γ-rays and neutrons. About 15 cm is required to eliminate γ-rays.

In general, poloidal section cameras suffer from back-scattered neutrons. Scattered neutron stem from the vessel and surrounding structure as well as from neutron camera shielding. Figure 1b and 1c shows the scattered neutrons on collimator channels of radial and diagonal camera respectively. The scattered neutron for the radial camera is constant and a slight increase when going from channel 13 to 21 for the diagonal camera. The ratio between scattered (energy threshold E_{TH} ∼ 1 keV) and uncollided neutrons are in range of 0.2-0.8 for both radial and diagonal cameras due to the interference of field of view with the central column region. The ratio of scattered to uncollided neutrons for the poloidal section camera is higher than that for the horizontal camera [4] due to the interference of sight lines with the central solenoid and the divertor plates and it does not allow to reduce by the variation of the collimator dimensions.

DETECTORS FOR THE NC UPGRADE

The neutron cameras developed for JET [5], MAST [2], etc. or planned for ITER [2] are employ scintillators as monitors for the collimated neutron fluxes. For the MAST prototype NC, liquid scintillators coupled to PMTs are used. Their signals are read out by digital transient recorder boards (12-bit 250 MSamples/s) and a charge comparison method is used for pulse shape discrimination, which allows for high neutron count rate. Liquid scintillators offer relatively high light-output and high detection efficiency. They permit separation between neutrons and γ-rays, allowing neutron spectrometry in a background of γ radiation. Due to these attributes, liquid scintillators coupled to PMTs are selected for the NC Upgrade as well. On the other hand, PMTs are sensitive to the high magnetic fields present in the MAST Upgrade, therefore silicon photomultiplier tubes (SiPMTs) will be considered as an alternative. SiPMTs are insensitive to the magnetic fields and can be operated at room temperature. SiPMTs have been coupled to the scintillator and used in the mixed neutrons and γ-rays detection [7]. Stilbene crystal scintillators are used in the JT- 60U [8] and they are one candidate for the ITER neutron camera [2]. Stilbene scintillator has a high light-output and have been used widely in mixed neutron and γ fields but they are subject to damage from thermal and mechanical shock. The results in the previous section show that neutron cameras are sensitive to scattered neutrons, thus it is necessary that the detectors can discriminate scattered neutrons from direct ones without losses in the efficiency. Taking these requirements into account, fission chambers based on ^{238}U are valid alternatives, since they offer a detection threshold on the neutron energies of ~ 1 MeV. Mostly, fission chambers are used for monitoring the total neutron yield, but in [6] the performance of fission chambers for the ITER neutron camera was studied. As a result, fission chambers can be used for a collimated neutron monitor with a high neutron efficiency, they do, however, not allow any kind of spectrometry. For this reason, to achieve a neutron monitor with the possibility of spectroscopic studies, diamond detectors are considered. The response function and neutron detection efficiency of liquid scintillator detectors has been modelled with MCNP. Simulations or tests of fission cambers and diamond detectors have not been performed in this work.

CONCLUSION

A design of the NC Upgrade in a poloidal section plane has been suggested. They are expected to yield the required uncertainty of 10 % and 1 ms time resolution in measuring neutrons for the MAST Upgrade plasma operations. The proposed collimator and detector dimensions provide high efficiency for measuring the neutron emissivity. The poloidal section camera has a clearer view on the emission profile from the central peak to the edge of the plasma than the tangential view of the horizontal camera. However, the performance of the poloidal section camera concerning spatial resolution and the possibility to reconstruct the plasma profile is not as good as for the horizontal camera. Furthermore, the ratio between scattered and uncollided neutrons is higher for the poloidal section camera than for the horizontal camera. Future work will include a more detailed comparison between the two geometries for different plasma scenarios and detailed simulations of different detector types and their performance in a neutron camera.

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REFERENCES

1. W. Morris, *IEEE Trans. Plasma Sci.* **40**, 682–691 (2012).
2. M. Cecconello et al., *Rev. Sci. Instr.* **81**, 10D315 (2010).
3. M. Cecconello et al, *Nucl. Fusion.* **52**, 094015 (2012)
4. S. Sangaroon et al., *40th EPS Conference on Plasma Phys. Helsinki*, **37D**, P5.124 (2013).
5. J. M. Adams et al., *Nucl. Instr. Meth. A* **329**, 277–290 (1993).
6. A. V. Krasilnikov et al., *Nucl. Fusion.* **45**, 1503-1509 (2005)
7. M. Foster et al., *IEEE Nuclear Science Symposium Conference Record*, N26-3 (2008).
8. M. Ishikawa et al., *Rev. Sci. Instr.* **73**, 4237-4242 (2002)