Conceptual design of a neutron camera upgrade for MAST Upgrade

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Abstract

An upgrade of the existing neutron camera is considered a high priority diagnostic for the physics exploitation at the Mega Amp Spherical Tokamak Upgrade (MAST Upgrade) particularly in the field of fast ions and current drive studies [1]. This paper describes the conceptual design of a neutron camera upgrade (NC Upgrade), composed of two sets of sight lines in horizontal planes, one in the equatorial and one in a down-shifted plane to view the off-axis plasma. Simulations of relevant performance parameters have been performed with the Monte Carlo code MCNP. The analysis has focussed on the optimization of the NC Upgrade design with respect to the detector geometry and collimator dimensions. The NC Upgrade performance has been validated for the main plasma scenarios expected for MAST Upgrade.

Introduction

The MAST spherical tokamak is used for physics studies contributing to research towards ITER and DEMO [1]. The MAST Upgrade will allow studies of off-axis current drive and fast-particle physics in ITER relevant plasma scenarios. As part of the MAST Upgrade, a significant increase of the neutral beam injection (NBI) heating power is envisaged from today's 5 MW to 7.5 MW and finally 12 MW [1], resulting in an expected considerable increase in fast ion populations and hence in the 2.45 MeV neutron yield. At present, MAST is equipped with a prototype neutron camera (NC), viewing the plasma through collimated sight lines [2]. The NC allows to measure the spatial distribution of the neutron emission and its evolution in time, providing information on the interplay between MHD activities and fast particles [3] and on the effect of off-axis current drive on fast particle redistribution [4]. However, due to the limited number of sight lines of the prototype instrument, data from a series of about 4-6 plasma discharges is needed to construct a field-of-view integrated neutron profile. On the basis of the experience and results from previous experimental campaigns, the conceptual design of a NC Upgrade is being developed. The optimization has been carried out taking into account both engineering limitations (available space, port flange positions/dimensions, interfacing issues, etc.) and physics aspects (plasma scenarios and shapes, diffusion coefficients, etc.).

Lines of sight and collimator geometries

The NC Upgrade design must fulfil the following requirements on the measurement of the neutron emissivity at MAST Upgrade: 10 % uncertainty on the number of counts for each sight line with 1 ms time resolution for neutron emissivities between 2×10^{11} and 2×10^{12} n $s^{-1}cm^{-3}$ (emissivity range expected for the operation of MAST Upgrade) [1]. In order to optimize the number of sight lines, the dimensions of the viewing cones and the spatial resolution, MCNP simulations have been performed and described in next section. The NC Upgrade will be located at MAST Upgrade sector 04. The design proposed here consists of two fan-shaped arrays (hereafter referred to as cameras) of cylindrical collimators embedded in a shielding in horizontal planes, one at Z = 0 cm (equatorial plane) and a second one at Z = -65 cm (down-shifted horizontal plane). In the equatorial plane, the plasma can be viewed without any interfacing issues. The equatorial camera consists of a set lines of sight (LoS), covering the plasma from inboard to outboard with a tangential radius or impact parameter, p = 50-120 cm. As an example, twelve LoS and their intersection with the neutron emissivity profile are shown in figure 1. In the down-shifted plane, however, the presence of ELM coils limits the field-of-view. The down-shifted camera has been chosen at Z = -65 cm in order to study the MAST Upgrade off-axis NBI at Z = +65 cm based on the expected fast redistribution of the injected fast particles. The down-shifted camera is designed to cover a plasma range of p = 60-110 cm.

MCNP simulations

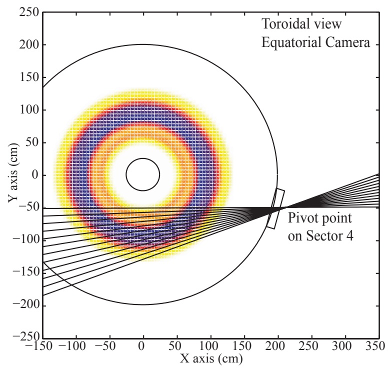

Figure 1: *12 LoS (in equatorial plane) plotted together with the neutron emissivity.*

The MCNP model contains the most recent MAST Upgrade geometry and materials. All structure not taken into account are expected to have a very small impact on the simulation results. The neutron source is a non-flux surface averaged neutron emissivity obtained by TRANSP simulations for relevant MAST Upgrade scenarios. It is represented as a toroidally symmetric neutron emissivity together with a simplified (Gaussian) DD fusion neutron energy spectrum. A detailed MCNP model of the NC Upgrade has been developed, consisting of: *i)* the collimators; *ii)* liquid scintillator detectors; *iii)* neutron shielding; *iv)* γ-ray shielding and *v)* magnetic shielding. Selected views of the model are presented in figure 2.

The distance between the MAST Upgrade vessel and the NC Upgrade position is the result of simultaneously: *i)* minimizing the impact of the MAST Upgrade poloidal magnetic field on the NC Upgrade photomultiplier tubes (PMTs); *ii)* minimizing the perturbing effect of soft-iron shield on the plasma confining magnetic field and *iii)* demands neutron count rates and spatial resolution. *i)* and *ii)* require a long distance while *iii)* demand a short one. The magnetic field shielding consists of soft-iron and μ-metal. In order to evaluate the magnetic field in the magnetic shielding, finite element method (FEM) calculations have been performed, using maximum coil currents of the expected MAST Upgrade operation. The number of sight lines affects the level of detail with which a field-of-view integrated neutron profile can be constructed. Here, cameras with 10, 12 and 14 sight lines are compared. The collimator radii are chosen to give the same overlap between neighbouring sight lines for all three cameras and the detector thickness is chosen to result in a constant count rate. The detectors envisaged for the NC Upgrade in this work are liquid scintillators coupled to PMTs which provide high efficiency and good n/γ separation and allow count rates in the MHz range. The radii of the cylindrical detectors match the collimators while the choice of the thickness is based on: *i)* the detector efficiency, obtained from MCNP calculations, which will affect the range of the measurable neutron emissivity and *ii)* the ratio between scattered and uncollided neutrons. The collimator radii (r) and length (L) are designed with the aim to give: *i)* a sufficient count rate for the expected neutron emissivities for a given detector position and thickness and *ii)* a good ratio between scattered and uncollided neutrons and between background γ-ray and neutrons. High density and purity polyethylene (HDPE) was selected for the neutron shielding due to high effectiveness as a moderating material. The shielding gives well-defined the sight lines (collimator geometries). The background γ-rays originate from: *i)* plasma reactions and *ii)* neutron capture in the HDPE shielding (E_γ = 2.23 MeV). The background γ-rays are shielded by lead. The lead thickness was varied in a range up to $\sim$ 15 cm in order to reduce the ratio between background γ-rays and total neutrons in one order of magnitude.

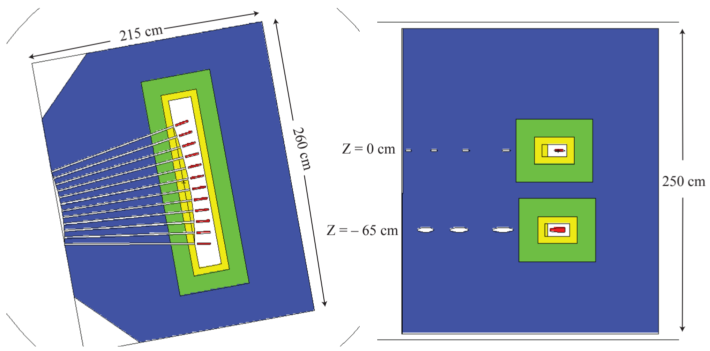

Figure 2: *MCNP model, HDPE (blue), lead (green), soft-iron (yellow), detector (red). (L) Z = 0 cm, (R) cut-view.*

Results and discussion

The proposed design of the NC Upgrade is a compromise between detector position, detector dimensions, number of sight lines and collimator dimensions as described in the previous section. The solution for the detector position is at 500 cm from the MAST Upgrade centre column. In order to reduce the magnetic field at the detector position, a combination of used magnetic shielding of 6 cm thick of soft-iron together with 2 mm thick of μ-metal is used, resulting in a field of 0.35 mT, which will not affect the gain of the PMTs. The combination of distance between vessel and NC Upgrade and the chosen soft-iron boxes thickness gives the perturbing effect to the MAST Upgrade magnetic field configuration inside the vessel, at major radius 90 cm, about 0.73 mT. The system consists of two cameras:

i) Equatorial camera: The number of sight lines is selected from the capability to construct the field-of-view integrated neutron emissivity profile. An example profile of MAST Upgrade plasma scenario C (diffusion coefficient 0 m^2/sec) [1] obtained with different number of collimators compared to the spatially collimated, line integrated, neutron emissivity profile is shown in figure 3. An array with twelve sight lines is selected for the equatorial camera, the design is combined with cylindrical collimator L = 115 cm, r = 0.82 cm and a detector thickness of 2.5 cm. The camera covers an angular field of 19.51° with 6.40 cm spatial resolution. The detector efficiency is 11 % for $E_n > 1.5$ MeV. The estimated neutron count rates ($E_n > 1.5$ MeV) in the plasma core are in range of 0.1-0.4 MHz (depend on MAST Upgrade plasma scenarios A.1 and C [1]). The ratio between scattered and uncollided neutrons is $\sim$ 0.15 for $p < 100$ cm while it is ten times higher at the plasma edge.

ii) Down-shifted camera: The design consists of eight sight lines with the same collimator length as for the equatorial camera, L = 115 cm. The combination between collimator radii r = 2 cm and detector thickness of 2 cm (detector efficiency is 9 % for $E_n > 1.5$ MeV) give the estimated neutron rates in range of 0.2-0.5 MHz. The camera covers an angular field of 13.88° with 7.24 cm spatial resolution. The ratio between scattered and uncollided neutrons is $\sim$ 0.5 for $p < 100$ cm while it is $\sim$ 2.5 at the plasma edge. With a 15 cm thick lead shielding for each camera, the ratio between background γ-rays and neutrons is $\sim$ 0.1.

Conclusions and outlook

A design for a NC Upgrade comprising two sets of sight lines in horizontal plane has been suggested. The cameras are expected to yield the required uncertainty (10%) and time (1 ms) resolution in measuring neutrons in the MAST Upgrade experiments. The proposed collimator and detector dimensions will provide high efficiency for measuring the neutron emissivity, as well as low contributions from scattered neutrons and background γ-rays. The future work, an updated MCNP model of the NC Upgrade shielding materials and the MAST Upgrade taking the interference with other diagnostics and structures into account will be established.

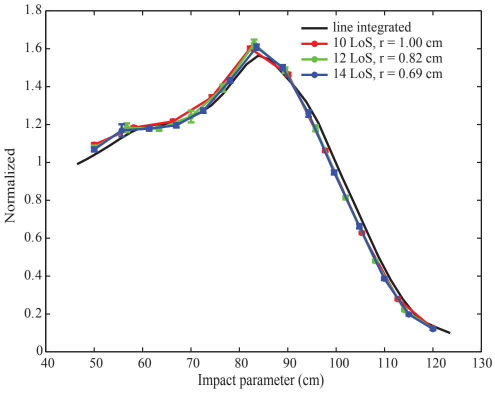

Figure 3: *Comparison of line integrated neutron emissivity profile and MCNP calculations.*

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