EUROfusion

EUROFUSION WPMST2-PR(16) 15256

M Rodriguez-Ramos et al.

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Preprint of Paper to be submitted for publication in
21st Topical Conference on High Temperature Plasma Diagnostics 2016

This work has been carried out 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. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

First absolute measurements of fast-ion losses in the ASDEX Upgrade tokamak[a)]

M. Rodriguez-Ramos[1,2,b)] , M. Garcia-Munoz[1,2,3], J. Galdon-Quiroga[1,2], J. Garcia Lopez[1,2], L. Sanchis-Sanchez[1,2], M.C. Jimenez-Ramos[2], J. Ayllon[2], P. de Marne[3], A.D. Dominguez[1,2], J. Gonzalez-Martin[2], A. Hermann[3], J. Rivero[2], B. Sieglin[3], A. Snicker[3], and the ASDEX Upgrade Team[c)]

[1] *Department of Atomic, Molecular and Nuclear Physics. University of Sevilla, Sevilla, Spain*

[2] *CNA (U. Sevilla, CSIC, J. de Andalucia), Sevilla, Spain*

[3] *Max-Planck-Institut für Plasmaphysik, Garching, Germany*

First absolute measurements of fast-ion losses have been obtained in the ASDEX Upgrade tokamak by means of absolutely calibrated scintillator based fast ion loss detector and infrared measurements. An instrument function that includes scintillator efficiency, collimator geometry, optical transmission and camera efficiency has been constructed. Absolute flux of Neutral Beam Injection (NBI) prompt losses has been obtained in magnetohydrodynamic (MHD) quiescent plasmas. ASCOT simulations are in fairly good agreement with FILD and IR measurements of the fast ion load.

I. INTRODUCTION

In fusion devices, fast-ions generated by external heating systems: NBI, Ion Cyclotron Resonance Heating (ICRH) and fusion born alpha particles constitute an essential source of energy and momentum. There are several fast-ion transport mechanisms that can have an impact on the performance of the heating systems affecting the heating and current drive efficiency and threatening the device integrity [1]. A good fast-ion confinement is essential on the road towards a burning plasma. Experimentally a good understanding of the fast ion transport mechanism can be obtained from direct measurements of fast ion losses at the plasma edge using a scintillator based Fast-Ion Loss Detectors (FILD). FILD systems [2] acts like magnetic spectrometers allowing energetic ions enter through the slit into the chamber and activate a scintillator material. The light emitted from the scintillator is transmitted through an optical system and imaged by a double system (camera+photomultipliers (PMTs)). Absolute measurements of the escaping ions are, however, not available due to the complex dependence of the scintillator efficiency with the impinging ion species and energies. In this work, we describe the procedure we have followed to calibrate the FILD systems of the AUG tokamak and give absolute values of fast-ion losses measured in NBI heated discharges in the absence of MHD fluctuations.

a)Contributed paper published as part of the Proceedings of the 21st Topical Conference on High-Temperature Plasma Diagnostics (HTPD 2016) in Madison, Wisconsin, USA.

b)Author to whom correspondence should be addressed: mrodriguez67@us.es

c)For authors' list, see U. Stroth et al., Nucl. Fusion 53, 104003 (Year: 2013).

II. CALIBRATION PROCEDURE

A. Characterisation of scintillator efficiency in a tandem accelerator

The scintillator efficiency in the hostile environment in which FILD sytem operates is still not fully understood. The characterization of the efficiency of the scintillator material has been carried out in the Spanish National Accelerator Centre (CNA), Seville, Spain [3], in particular, in a 3 MV tandem accelerator. An ion source provides different ion species (deuterium, protons and helium particles) to irradiate the sample. These tests were made in a scattering vacuum chamber attached to the accelerator and equipped with a photonic diagnostic system comprised by a silica optical fiber of 1 mm diameter fixed to the vacuum chamber and a spectrometer QE6500 (Ocean Optics Inc.). In particular, the ion luminescent efficiency of the phosphor $SrGa_2S_4{:}Eu^{2+}$ (named as TG-Green) was analyzed irradiating with light ions with energies between 1-3 MeV at room temperature. The beam fluxes used to irradiate the scintillator were estimated $\approx 4.0 \times 10^{10}$- 2×10^{11} ions/cm^2s. It was found that the photon yield is not linear with the energy deposited into the materials (Fig 1.a). The energy of ions injected into the plasma by the AUG-NBI system are below 100 keV and are not accessible in our accelerator. However the experimental results can be well reproduced using a simple ionoluminescence model knows as the Birks law [4]. This model can be employed to predict the sample response for other ions and/or energies of interest. A more detailed study can be found in the paper [5].

B. The FILD weighting function

The final ion pattern on the scintillator plate depend on the 3D geometry of the entire FILD head. The probe presents a three-dimensional structure (pinhole + slit entrance) acting as a particle collimator that restricts the incoming ion orbits.

The procedure was the characterization of the collimator factor f_{col} defined as the ratio between the number of ions reaching the collimator pinhole and the number of ions that hit the scintillator plate. For this purpose Monte Carlo simulations with the orbit-tracing FILDSIM code [6] has been performed. The results obtained after the simulations have been used to relate the flux of escaping ions that reach the pinhole (which can be related to the losses at the first wall) with the flux of incoming ions at scintillator plate. Results show that actual AUG FILD head probe design induces a reduction of about $99-97$ % (Fig 1.b). To reproduce the velocity space distribution measured at the scintillator plate, using a simulated escaping ion distribution at the pinhole, a weighting function $W(E,\Lambda)$ which depends on the energy and the pitch angle of the particles has been constructed:

$$\Gamma^{Sim}_{scintillator} = \Gamma^{Sim}_{pinhole} \times \underbrace{f_{col} \times R_E \times R_\Lambda}_{W(E,\Lambda)} \tag{1}$$

where R_E and R_Λ are the resolution in energy and resolution in pitch angle that define the dimensions of the spot (Ω) in the scintillator plate.

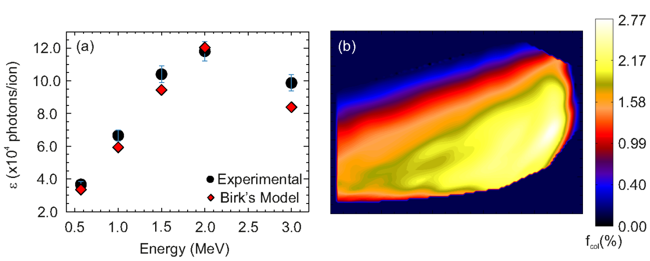

FIG. 1. (a) Experimental (black) and calculated (red) yield data for deuterons particles for the TG-Green scintillator at room temperature. (b) Collimator factor values obtained for the scintillator plate region by simulation with FILDSIM code.

C. Characterization of the optical path and efficiency of light acquisition systems

The light transmission of the FILD optical path has been estimated using an integrating sphere (Labsphere Unisource 1200). The detector head was replaced by the integrating sphere, obtaining a well known and uniform light source. A bandpass filter with a transmission wavelength of 525 nm and a FWHM=3.7 nm is used to reproduce the scintillator spectra emission. The quantification of the absolute photon flux Φ_{IS} (number of photons per unit time, and per unit area) reaching the camera in terms of the spectral radiance $L_{e,\Omega,\lambda}(\lambda)$ of the integrating sphere (Fig 2.a) and the transmission coefficient $T(\lambda)$ of the optical filter was obtained as:

$$\Phi_{IS} = 4\pi \int L_{e,\Omega,\lambda}(\lambda) \times T(\lambda) d\lambda \approx 7.83 \cdot 10^{18}\ \frac{photons}{s \cdot m^2} \tag{2}$$

The light pattern produced by the integrating sphere was recorded by the camera and extracted as a calibration frame (Fig 2.b). The exposure time δt of the camera has been selected to obtain an intensity of the pixels approximately equal to the half dynamic range of the camera. The pixel intensity I_{IS} of the calibration frame and the integrated photon flux Φ_{IS} allows to obtain a calibration factor for each pixel:

$$\xi = \frac{\delta t \cdot \Phi_{IS}}{I_{IS}} \approx 1.74 \times 10^9\ \frac{photons}{Counts \cdot cm^2} \tag{3}$$

This expression relates the counts from the CCD frame with the number of photons hitting the sensor of the camera.

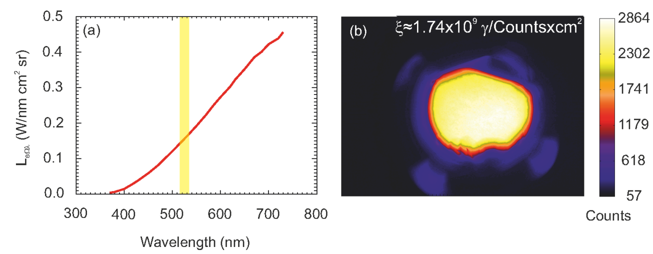

FIG. 2. (a) Wavelength dependence of the spectral radiance of the integrating sphere (red). The yellow column represents the ROI of the bandpass filter. (b) Calibration frame (colors have been added artificially) to calibrate the FILD detector. The homogeneous central region (yellow) presents a pixel intensity ≈ 2700 counts for a exposure time of 6 ms.

D. The FILD instrument function

The calibration of the light acquisition system, the absolute yield of the TG-GREEN and the weighting function of AUG-FILD has been used to develop an instrument function that converts the experimental fast ion loss signals into absolute fluxes for each pixel at position (p, q). If the pixel signal is $I(p,q)$ take during an exposure time Δt, the empirical equation is introduced as follows

$$\Gamma^{Exp}_{pinhole} = \frac{1}{\epsilon \times f_{col} \times \Delta t} \iint_{\Omega(E,\Lambda)} \xi(p,q) \times I(p,q) \tag{4}$$

III. RESULTS

A. Absolute flux of NBI prompt losses in AUG

The instrument function obtained here has been applied to NBI prompt loss signals obtained in dedicated experiments at the AUG tokamak. The absolute fluxes of fast ion losses have been obtained in discharge AUG # 30810 with B_t = -2.35 T , I_p = 1.003 MA and NBI as main heating system and fast particle source ($P_{Inj} \approx 2.5$ MW). Typical trajectories of the fast ions measured with the AUG FILD (FILD 1, located just below the midplane at the toroidal angle of ≈ 169 °, Z=0.33 m and a radial position R=2.161 m) are plotted in Fig 3.a and Fig3.b.

The frame was taken at t=2.70 s, at this time, the total magnetic field at the head detector was B≈1.73 T. One clear spot at a gyroradius of 2.8 cm and a pitch angle of ≈ 55° is visible and allows us to determinate the energy of fast ions that was estimated in ≈ 60 keV corresponding to AUG NBI # 3 (Fig 3.c).

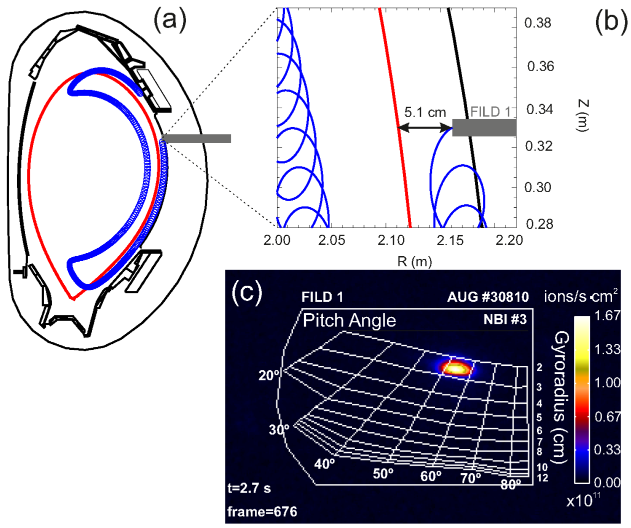

FIG. 3. (a) Poloidal view of one banana orbit with E= 60 keV and Λ = 55 °. (b) FILD 1 position at AUG tokamak showing the distance between the detector and the separatrix (shown in red). (c) Ion flux in the scintillator plate. The picture shows in white the strike map necessary to identify the velocity space of the escaping ions. The visible spot is a typical prompt-loss signal.

Fig 4.a shows the temporal evolution of absolute flux of losses measure with FILD 1. The absolute fluxes obtained here in FILD-1 are in good agreement with IR measurements [7] of the detector head. A clear correlation is found between the heat flux (≈ 2 MW/m^2) and the FILD signal (≈ 0.2 MW/m^2). The NBI prompt losses in this discharge have been modeled with the full orbit code ASCOT [8]. 10^6 test particles were followed until they hit a plasma facing component or slow down to the background thermal energy. The simulated NBI heat load (< 1 MW/m^2) is presented in Fig 4.b.

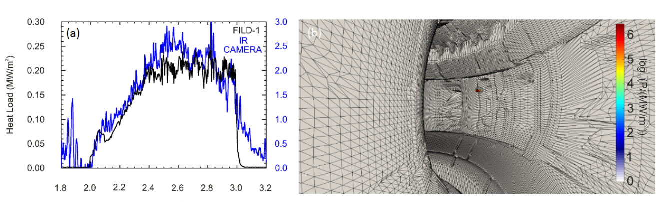

FIG. 4. (a) Temporal evolution of the absolute prompt losses measured with FILD-1 (black) and IR camera (blue) for discharge AUG-30810. (b) Wall power loads due to NBI #3 in AUG discharge #30810 at t=2.7 s obtained with ASCOT.

A good agreement of the absolute flux obtained here in FILD-1, the IR measurements of the detector head and the ASCOT simulations have been obtained.

IV. SUMMARY

The absolute flux of NBI prompt losses measured by a FILD system in the AUG tokamak has been obtained for the first time. A FILD instrument function that includes the scintillator efficiency, collimator geometry, optical transmission and camera efficiency has allowed to estimate the absolute flux of ions in FILD velocity space. IR measurements and ASCOT simulations of the heat load in the detector head are in fairly good agreement with the absolute heat load obtained by FILD measurements.

ACKNOWLEDGMENTS

This research was supported in part by the Spanish Ministry of Economy and Competitiveness (RYC-2011-09152 ,FIS2015-69362-P and ENE2012- 31087), the Marie Curie FP7 Integration Grant, PCIG11-GA-2012-321455, within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014–2018 under grant agreement number 633053 and the V Plan propio de la Universidad de Sevilla (VPPI-US).The views and opinions expressed herein do not necessarily reflect those of the European Commission

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