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Measurements and Modeling of Impurity Source Distributions from the Tore Supra Outboard Pump Limiter[†]

C.C. Klepper, J.T. Hogan, S.J. Tobin[‡], R.C. Isler

Fusion Energy Division, Oak Ridge National Laboratory

Oak Ridge, TN 37831-8072

D. Guilhem, W.R. Hess, P. Monier-Garbet

Assoc. EURATOM- CEA, DRFC/SPPF, Centre d'Etudes de Cadarache

F-13108 Saint Paul-lez-Durance, France

ABSTRACT

An experiment has been carried out to study impurity generation processes on an inertial limiter on Tore Supra. It is part of a plan to assemble a more detailed integrated picture of impurity generation at the inner wall, the outboard and vertical pump limiters, and the heating and current drive antennas. A system has been implemented to permit quantitative measurement of impurity sources from the outboard limiter in Tore Supra. Data are presented for a representative case in which the limiter is isolated as much as possible from connection with other Tore Supra plasma-facing components. The data are compared with results from the Monte-Carlo SOL impurity transport code BBQ, in an attempt to identify the mechanism for impurity release. Evidence of chemical sputtering as an important impurity source is seen.

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Introduction

The problem of impurity generation presents a fundamental limit to long pulse, steady-state operation. To characterize the impurity source accurately in a tokamak experiment, it is necessary to understand the interrelationship of sources from all the plasma-facing components (PFCs). In Tore Supra, these include the inner wall, the outboard and vertical pump limiters, as well as the heating and current drive antennas. As is well known, however, impurity transport at the plasma edge is not well understood and is hard to measure experimentally. Measurement and interpretation of edge impurity generation and transport are complicated because the sources are very localized and the atomic and molecular processes are complex. The highly localized nature of the sources, and of the associated optical emission, implies that good spectroscopic viewing access and high spatial resolution are required. Since the spatial distributions of charged impurities are the typical observables, interpretation in terms of generation processes requires the use of codes to translate the predicted distribution of impurity densities from a given source into an observed distribution of emission. It also requires that the codes used in the interpretation include the specific geometry of PFCs in great detail.

This paper describes a study conducted on Tore Supra in which small plasmas were created to isolate the outboard pump limiter as the most important PFC. Complementing previous studies of impurity generation at the Tore Supra inner wall [1], [2] and the neutralizer plate of the semi-actively cooled (Phase II) outboard pump limiter [2], [3], this study allows an examination of the characteristics of impurity generation at the face of the outboard limiter in isolation from other interactions. Since there is no direct view of this limiter from an external port in the machine, the design of a special endoscopic imaging system was required, and this is described below.

For modeling and interpretation of the data the impurities code BBQ is used. This code incorporates a 3-D Monte-Carlo description of both neutral and charged impurity transport. The "physical" model in the code is patterned after that in the LIM code (P. Stangeby et al. [4]). As is well known, the value of such codes is determined by the level of detail of geometry which is included, and the detailed, "as-built", geometry of Tore Supra is incorporated in BBQ. For the impurity generation processes, such as physical and chemical sputtering, the recommended values of Eckstein et al. [5] are employed. BBQ calculates the evolution of CH₄ breakup products (chemically produced impurities) using the data base of Erhardt and Langer [6]. The CH₄ breakup model in BBQ was compared with low density experiments conducted in PISCES [7]. The code calculates spatial distributions of $C^0 \rightarrow C^{+6}$ (and of CH₄ $\rightarrow$ CH) arising from impurity generation.

This experiment was carried out with an inertially cooled, nonpumping outboard limiter (Phase I). The Tore Supra semi-actively cooled (Phase II) pump limiter used in previous experiments had been removed to repair damage incurred in a previous experiment. The front face of the Phase I inertially cooled limiter is shaped identically to that of the new, actively cooled Phase III pump limiter, which is presently installed on Tore Supra [8]. The Phase I limiter is a monoblock of isotropic graphite and is not cooled. As a result, the plasma contact with the outboard limiter module was limited to about 4 s, and time-dependent effects were anticipated because of the increasing temperature of the limiter.

The shape of the outboard limiter was designed from optimization studies that accounted for the detailed magnetic flux geometry, including ripple effects, to optimize the heat removal capability, while keeping the heat flux to the leading edge within a manageable range [9], [10], [11]. Figure 1 shows the predicted toroidal heat flux distribution for the design case of $R = 2.38$ m, $a = 0.75$ m on the limiter [11]. Note in Fig. 1 that maximum

limiter temperatures are expected near the “crown” of the front face (at 0.10 to 0.15 m toroidally from the tangency point) and at the tip of the leading edge.

Experimental Setup

An existing endoscope system previously used for infrared (IR) measurements was modified for imaging in the visible range of the spectrum. The modification was designed such that the internal IR optics could be reproducibly replaced by the visible optics, and vice-versa. In addition, a beam splitter was introduced into this system so that the light could be directed simultaneously to a CCD camera and to a set of optical fibers. This way, the CCD camera provides the high spatial resolution for the entire limiter, while the optical fibers, coupled to a dedicated visible spectrometer, provide the absolute calibration and the spectral resolution. Figure 2 shows a schematic of this system. The CCD camera was equipped with a filter wheel, containing interference filters for the D_{α} (6561 Å), CII (5150 Å) and CIII 4647 Å lines, respectively. By using an asynchronous controller for the CCD camera, the integration time could be varied over a large range (typically 0.2 to 200 ms) to control the effective gain of the camera. The limited dynamic range of the CCD camera required duplicating each plasma shot, so that the image could be optimized for either the bright leading edge or the dimmer front face. The spectrometer was equipped with an Optical Multichannel Analyser (OMA). Exposure times varied between 0.1 and 1.5 s, depending on the plasma conditions and the spectral line observed.

Experimental results

This campaign included electron density scans in the range of 1.6 to $3.5 \times 10^{19} \text{ m}^{-3}$ (volume averaged) and a plasma current scan in the range of 0.8 to 1.49 MA in D_2 plasmas. For each of these conditions, all at $B_T = 3.7 \text{ T}$, sets of similar shots were pro-

duced, so that each of the three spectral lines (CII, CIII, and D_α) could be monitored with the spectrometer and with the CCD camera simultaneously.

In this paper, we present data from the case of $\langle n_e \rangle = 3.0 \times 10^{19} \text{ m}^{-3}$ and $I_p = 1.24 \text{ MA}$. An apparent increase in the emission at the limiter leading edge was observed in the CCD filtered images, as a function of time. This increase was later shown, by means of the spectrometer data (Fig. 3), to be due to increases not in the line intensity, but in the underlying continuum caused by significant heating ($>1000^\circ\text{C}$) of the limiter. Thus, interpretation of the data requires a separation of the effects of continuum and line radiation. Here we restrict our analysis to times early enough in the limiter heating phase that the continuum radiation is not yet dominant (i.e., to $t \leq 6 \text{ s}$ in the discharge, where limiter heating begins at $t = 4 \text{ s}$).

A false color image of the spatial distribution of CII at $t = \sim 6 \text{ s}$ is shown in Fig. 4. Note that the maxima in emission occur at the locations where the heat flux and limiter temperature are expected to peak (Fig. 1). Such maxima were also seen in the D_α images, but not in the CIII images. Since CII emission is more closely tied to the impurity neutral source than CIII, this may be taken as an indication, independent of modeling, as to the localization of the impurity source. In this case the emission appears to be closely correlated with the expected maxima in limiter temperature distribution, and this gives an indication that chemical sputtering may be involved for this data set.

Modeling results

Modeling of this data set with the BBQ code has been carried out to compare the predicted CII and CIII distribution with those observed. The code requires the specification of a number of parameters describing SOL transport. For example, for the C diffusivity,

$D_{\perp} = 1 \text{ m}^2/\text{s}$ is assumed. Background plasma parameters are obtained from Langmuir probe data and the flux surfaces from magnetics. The code predicts the spatial distribution of $C^{n+}(\rho, \phi, \theta)$ from an assumed source of combined chemical and physical sputtering. The ratio of ionization to photon events (S/XB) is taken from [12] to generate a distribution of CII and CIII emission. The result is a predicted distribution of impurity light. Figure 5 shows the predicted distribution of CII emission for the case of Fig. 4 assuming only a physical sputtering source. A combined physical and chemical sputtering source results in the predicted distribution shown in Fig. 6. Qualitatively, the occurrence of a sharp peak at the limiter leading edge and also on the limiter crown requires a chemical sputtering source. An total ion flux of 50 A (or 50 torr l/s) and a 70:30 ion to electron drift-side asymmetry were assumed for these modeling runs.

Discussion and Conclusions

We have examined the spatial distribution of impurity sources on the front face of the Phase I outboard limiter for the simple case of a small plasma, which is only in contact with this limiter. Using the BBQ code, we can successfully model the measurements when we include chemical sputtering in the impurity generation processes. The estimated surface temperatures (T_{surf}) of the limiter, from IR camera images taken during similar shots, were in the range 625 to 795°C on the leading edge and about 600°C on the front face. In such a temperature range, chemical sputtering is expected to be significant (see Roth et al. in [5]). Although, in the literature, chemical sputtering data are limited to ion fluxes several orders of magnitude lower than those encountered in a tokamak limiter, previous results on the Phase II pump limiter showed this process to be important near the neutralizer plate [3]. There, the ion flux was measured to be about $2 \times 10^{19} \text{ ions/cm}^2/\text{s}$.

The oxygen content is normally negligible in Tore Supra, especially since boronization became a standard procedure. It is therefore assumed that oxygen plays no role in the sputtering process. The strong dependence of the chemical sputtering process on T_{surf} [5] is primarily responsible for the large difference figures 5 and 6. The expected large difference in the energies and ionization path lengths of molecules created by chemical sputtering to mostly atomic C generated by the physical sputtering mechanism also plays a large role.

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Figure Captions

Figure 1. Shape of the toroidal cross-section of the limiter and predicted heat flux distribution for the design case of $R = 2.38$ m, $a = 0.75$ m for various values of the heat flux decay length (λ_q) [11].

Figure 2. Schematic of the endoscopic optical imaging system, which permits simultaneous 2-D spatial imaging and calibrated spectra.

Figure 3. Evolution in time of the spectrum containing a set of CII lines near $5140 \text{ \AA}$, showing the increase in the continuum due to the blackbody radiation. The zero reference level on both sides of the spectrum is a result of the size of the intensifier, which is smaller than the photodiode array of the OMA.

Figure 4. False color image of the measured spatial distribution of CII at $t \sim 6$ s.

Figure 5. False color image of the predicted (with BBQ) spatial distributions of CII assuming only physical sputtering and (b) both physical and chemical sputtering.

Figure 6. False color image of the predicted (with BBQ) spatial distributions of CII assuming both physical and chemical sputtering.

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Relative heat flux distribution

Klepper et.al, Fig. 1

Klepper et.al., Fig. 2

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Klepper et.al., Fig. 3

Klepper et.al., Fig. 4

Klepper et.al., Fig. 5

Klepper et.al., Fig. 5/6

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