Ultrasoft X-ray Measurements of Impurity Levels in NSTX*

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1. Introduction

The soft X-ray emission from hot plasmas can be used to determine the impurity levels and profiles [1]. This information is operationally important and can also provide information about the local particle transport. With central electron temperatures in the 0.5-1.5 keV range, the bulk NSTX emission is in the ultrasoft X-ray (0.1<E<2 keV) range. Three arrays of absolute photodiodes (one fan of 16 vertical chords and two fans of 16 horizontal chords) and a photometrically calibrated grazing incidence spectrometer (GRITS) measure this emission [2]. The arrays can be independently filtered in several spectral ranges, being mainly used for imaging of MHD fluctuations up to 100 kHz in the plasma core and periphery. Here we report the application of these diagnostics for an estimate of the impurity concentration and profiles in ohmic and auxiliary heated NSTX plasma.

2. Spectroscopic data

For the present measurements the arrays have been operated in a 'spectroscopic' mode, in which each array is differently filtered. 0.3 μm Ti foils transmitting the strong C V and C VI resonance lines between 300-400 eV are used to measure the peripheral profiles, while 10 μm and 100 μm Be foils with 0.6 keV and 1.2 keV cutoff energies respectively, are used for the core.

The limited radial and angular coverage of the system and the fact that several of the outboard vertical chords are presently obstructed by in-vessel structures make the tomographic inversion of the USXR data difficult. Instead, we assume that the emissivity is described by a radially dependent flux surface function, which is fitted using the measured USXR profiles and the magnetic surfaces determined by EFIT reconstruction. A sin θ, cos θ

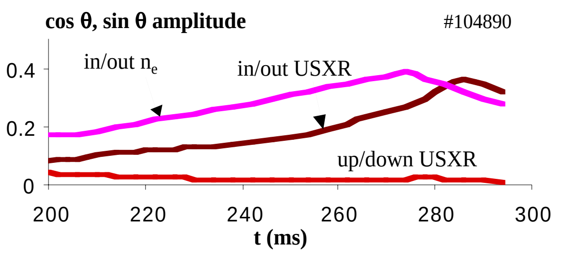

Fig.1 Evolution of the in/out and up/down asymmetry of the E >0.6 keV emissivity and the in/out asymmetry of the electron density, defined as $n_e(125\ cm)-n_e(55\ cm)/n_e(R_0)$

poloidal dependence is allowed to describe eventual up/down and in/out asymmetries. The asymmetries were assessed by operating the USXR system with identical filters on each array. The core emissivity appears up/down symmetric in most ohmic and auxiliary heated discharges, while significant in/out asymmetries can develop in NBI heated discharges. These seem to correlate with electron density asymmetries measured by the Multi-Point Thomson Scattering (MPTS) system (Fig. 1). The peripheral emissivity exhibits ≈ 10-20% up/down asymmetry and occasionally larger in/out values. For the impurity profile estimates we use therefore mainly the horizontal views and neglect the up/down asymmetry. Typical core profiles for ohmic and NBI heated discharges shown in Fig. 2 evidence a striking difference between the two cases.

Concerning the peripheral profiles, a notable feature is the presence of substantial USXR emission outside the closed flux surfaces in all plasmas, except the H-mode and early RF heated discharges (R. Maingi *et al.*, these proceedings).

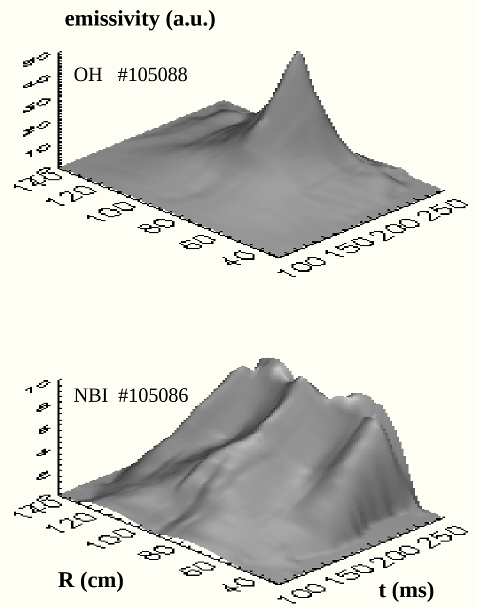

Fig.2 Evolution of the E >0.6 keV emissivity in consecutive ohmic and NBI heated discharges

The USXR spectrometer covers the 10-350 Å range with ≈ 1 Å resolution. Calibrated spectra indicate that after boronization (D. Mueller *et al.*, these proceedings) the dominant impurities are C and B, with a small fraction of O and occasional F and Fe. Since the spectrometer views the plasma across the heating neutral beam, a simple estimate of the line-of-sight C: B: O ratio can obtained from the intensity ratios of their respective H_α (Δn=2-3) transitions, after correcting for the Z-dependence of the CX cross section. Typical values are 1: 0.2-0.3: 0.05-0.15, with the O fraction steadily decreasing with run time. The more detailed simulations below, as well as recent VUV spectra confirm these ratios.

3. Impurity emission model

Due to the admixture of lines and continuum emission at sub-keV temperatures and the presence of several impurities, a relatively involved model is needed to simulate the USXR profiles in NSTX. First, *ab-initio* line emission radiative coefficients are derived for all the charge states of the above impurities sing the HULLAC atomic physics package [3]. The calculations include levels up to n=5. The recombination continuum is derived as in [1]. Impurity charge state distributions (CSDs) are then computed by the MIST transport code [4], using the MPTS n_e and T_e profiles as input. The one-dimensional MIST quantities are mapped onto (R, Z) space using the EFIT computed flux surfaces. Charge exchange is included in the model, since it influences the peripheral CSD in colder plasmas. Although the neutral density is not yet measured in NSTX, several line intensity ratios in the GRITS spectrum (e.g., C V $1s^2$-1s2p/C VI 1s-2p) appear to constrain this density to values typical for a large device ($\leq 0.1\ n_{eSOL}$).

Finally, the diffusive and convective transport coefficients D and V (and implicitly the impurity profiles) are varied to reproduce the measured USXR profiles and the calibrated GRITS spectra. Typical values for the fit are D ≈ 0.3-0.7 m^2/s and V of a few m/s. An example simulation is shown in Fig. 3, together with the Z_{eff} estimated from the visible bremsstrahlung measured during background exposures of the MPTS detectors. Agreement is evident for the core, while the edge USXR values are lower. We observe however, that the USXR result is more consistent with the low edge radiative power measured by bolometry.

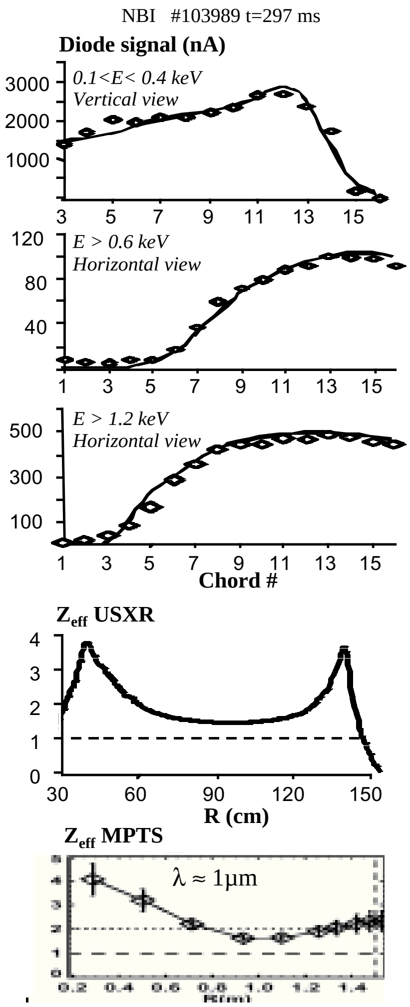

Fig.3 Experimental (†) and simulated USXR signals and best fit Z_{eff} profile. The Z_{eff} profile derived from the long wavelength continuum is also shown.

In conclusion, the modeling points to quite good wall condition in NSTX, with typical central impurity content after fresh boronization of 1-1.5% C, 0.25-0.5% B, 0.05-0.3% O, 0.03-0.1% F, and negligible metals. The impurity concentration outside the core is a few times larger and can also be significantly larger than above during RF heating.

4. Impurity profiles and correlation with MHD

Using the above model we compute the impurity profiles for the two discharges in Figure 2, both having 1 MA current flat top. The results in Figure 4a clearly indicate impurity accumulation in the core of the ohmic plasma. A large amplitude 1/1 mode localized at r/a ≈ 0.35 develops soon after the impurity peaking, typically followed by a sawtooth crash or an Reconnection Event (RE), which expels the impurities from the core. The impurity accumulation appears to occur *inside* the mode radius. This scenario seems common to most of the ohmic discharges in NSTX. The association between impurity accumulation and the 1/1 mode has been observed also in other devices.

More unusual are the impurity profiles in the NBI discharge (Fig. 4b). A pronounced 'well', with increasingly steep walls develops in the core. The well is often associated with the appearance of two closely localized MHD perturbations, both rotating in the ion direction, but with very different frequencies (Fig. 5). The estimated radial position of the modes approximately coincides with the top of the walls of the impurity 'well'. The transport coefficients cannot be well estimated from our steady-state simulations. However, the radial dependence of the impurity flux is physically meaningful. We find that modeling the 'well' requires a significant discontinuity in this flux at approximately mid-radius.

In conclusion, the presence of steep gradients in the core impurity concentration, together with the sheared MHD mode rotation, may indicate the presence of an internal transport barrier. Interestingly, neither the USXR observations nor the EFIT computed q-profiles show indications of shear reversal.

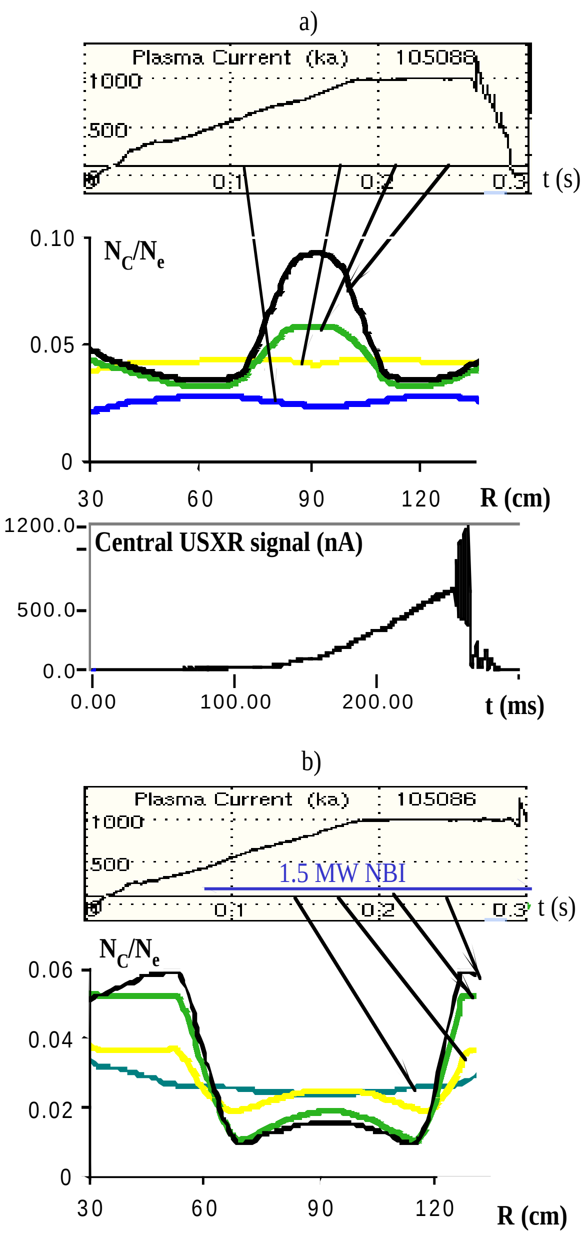

Fig.4 Evolution of the carbon concentration profile in ohmic (a) and NBI (b) heated discharges.

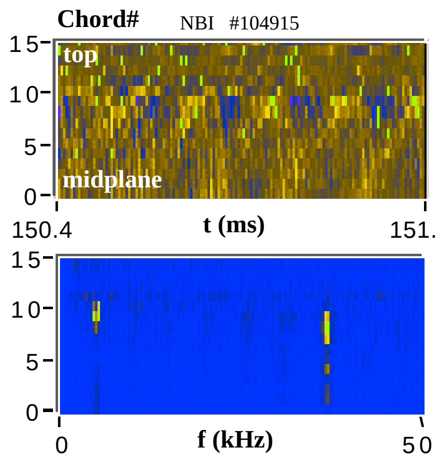

Fig.5 Slow (m=2) and fast modes observed together with the hollow impurity profiles, plotted in the time and frequency domain.

Similar 'wells' in the impurity profile and sheared MHD rotation are observed in RF heated discharges in He, though not in D_2 ones. This seems to suggest that the more efficient heating observed in He (J. Hosea *et al.*, these proceedings) might be transport related.

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