Edge transport measurements with the new multi-energy soft-x-ray diagnostic on NSTX

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NSTX is a large spherical torus designed to study plasma confinement and stability at low aspect ratios. Recent research on the device has focused on the plasma edge, as particle transport in this region has a large impact on global confinement. The effects of lithium-coated PFCs and 3D magnetic field perturbations on edge transport are of particular interest. With steep gradients in the edge, radial transport measurements require diagnostics with spatial resolution on the order of the ion gyroradius ($\sim$ 1 cm). Sub-millisecond time resolution is required for perturbative transport techniques and to study transients such as ELMs. Measuring transport with this high resolution in the sub-keV plasma edge is quite challenging.

To address this challenge, the JHU group has developed a multi-energy soft-x-ray (ME-SXR) diagnostic. This instrument provides an SXR emissivity measurement with course spectral resolution and fine spatial and time resolution. The system consists of five 20-channel silicon photodiode arrays, each with a view of essentially the same plasma volume. Four arrays have different foil filters (currently 0.3 μm Ti, 5 μm Be, 15 μm Be, and 50 μm Be) to provide 4-color spectral resolution, and the fifth array, with no filter, is used for bolometry. The filters discriminate line emission from groups of impurity ionization states; an example using neon is shown in Fig. 1. For measurements of neon puffed into the plasma edge, the bolometer signal is dominated by L-shell emission, while the 5 μm Be filter picks up primarily K-shell lines (H-like and He-like neon). The 50 μm Be array measures continuum emission from fully-stripped neon. Each array has a mid-plane tangential view of the plasma edge with radial coverage from $r/a \sim$ 0.6 to the scrape-off layer, with a radial resolution of 1 cm. Variable-gain preamplifiers produce a signal with high time resolution, ranging from about 10 kHz for high gain to greater than 100 kHz for low gain. Second-stage amplifiers are used to further boost the signal for digitization. In conjunction with other impurity-monitoring spectrometers, such as the

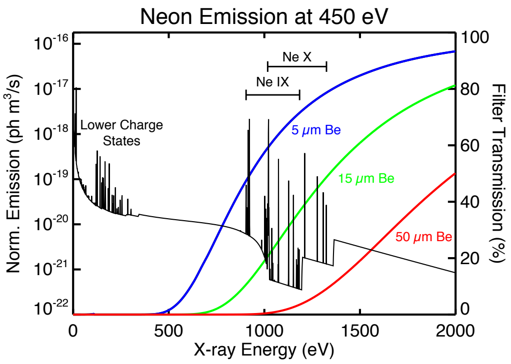

Figure 1: Filter transmissions overlaying neon emission from a 450 eV plasma. The bolometer measures the entire spectrum.

transmission-grating based imaging spectrometer (TGIS) [1], the ME-SXR arrays can provide fast T_e and impurity density measurements for transport calculations. A description of the technique now being implemented to quantify impurity transport in the plasma edge follows.

To model the particle transport of an injected impurity, we use the STRAHL 1D impurity ion radial transport code [2]. For a given impurity, each ionization state is described by a transport equation with a flux-surface averaged diffusion coefficient $D(r,t)$ and convective velocity $v(r,t)$. For neoclassical transport, the code uses NEOART [2] to compute D and v as a function of poloidal angle, then computes the flux-surface average. For anomalous transport, flux-surface averaged values are provided by the user. The particle source/sink term for each ionization state depends on the density of neighboring states through the rate coefficients for ionization, the recombination coefficients for radiative and di-electronic recombination, and the recombination coefficients due to charge exchange. These coefficients, along with x-ray emission coefficients, are obtained from the ADAS atomic database [3]. Along with D and v, the third free parameter in this transport model is the source of neutral impurities atoms, both directly from the impurity injection and from divertor and vacuum vessel wall recycling. A simple synthetic diagnostic uses the ionization state distribution of impurities from STRAHL and computes the expected x-ray intensity from continuum and line emission.

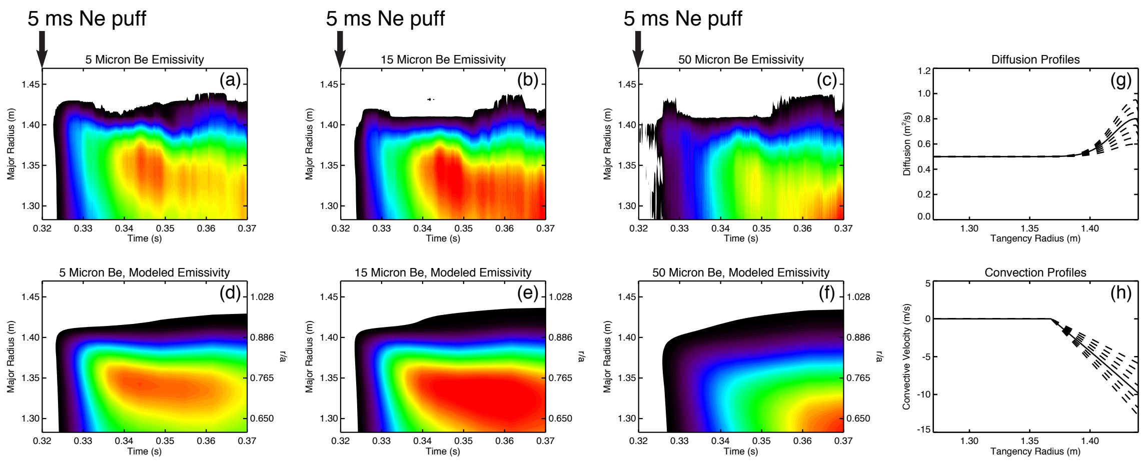

Figure 2: (a-c) Measured x-ray emissivity from ME-SXR. (d-f) Simulated x-ray emissivity from STRAHL. (g-h) Diffusive and convective radial profiles used to generate simulated data (solid lines) and modeled data for comparison (dashed lines).

Tests of the ME-SXR system have been performed, and preliminary data for perturbative impurity transport measurements were collected. Fig. 2(a-c) shows high-resolution (1 cm spatial, 0.1 ms temporal) filtered SXR emissivity measurements following a short, 5 ms puff of neon gas at the outboard midplane. The measured signals exhibit a high signal-to-noise ratio despite photodiode currents of only 10’s of nanoamps. Emissivity is obtained by inverting the measured line-integrated x-ray intensity using a matrix inversion technique [4]. Using STRAHL and the synthetic x-ray diagnostic, time-evolving emission profiles have been generated that closely resemble the measured data, as seen in Fig. 2(d-f). Previous estimates of the transport coefficients [5] were used to establish guesses for the *D* and *v* profiles, shown by the solid lines in Fig. 2(g-h). This dataset did not include the bolometry array, so a core bolometer was used in its place to provide a rough constraint on the neutral impurity source term for this preliminary transport analysis. The importance of the bolometer, which measures emission from low ionization states of neon and thus places a constraint on the source term of the higher charge states measured with the filtered arrays, is demonstrated in Fig. 3. The effects of transport and impurity source on x-ray emissivity are coupled; the source must be known to determine the transport coefficients.

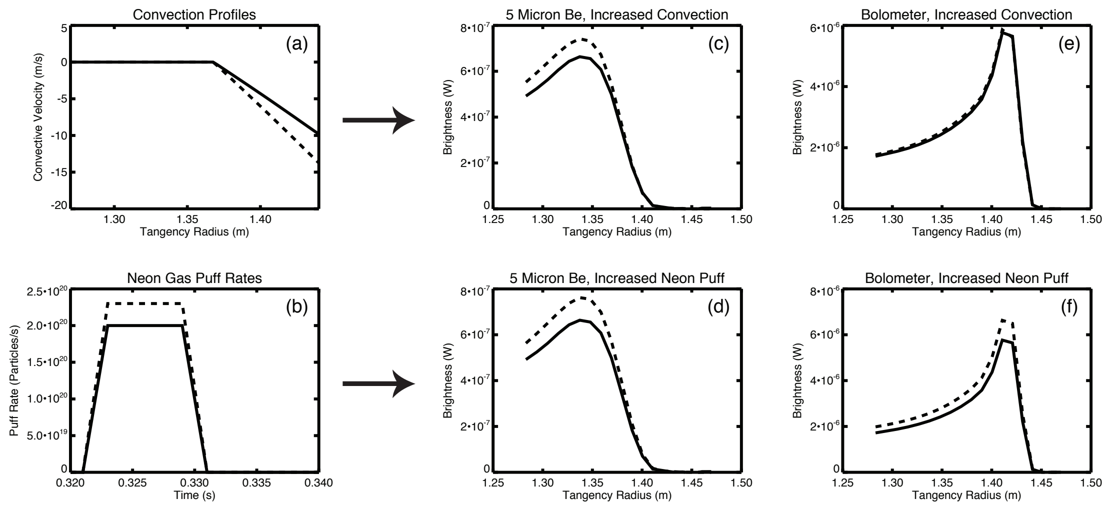

Figure 3: Increases in (a) the inward convection and (b) the gas puff flow rate appear to have the same effect on (c-d) the 5 μm Be filtered brightness, shown here 50 ms after the start of the gas puff. However, the effects on (e-f) the bolometry signal 50 ms after the puff are quite distinct.

To solve for the transport coefficients more precisely, a chi square minimization procedure is now being developed to fit the model to the measured data by adjusting the radial *D* and *v* profiles as well as the neutral source term. Note that on the time scale of the gas puff perturbation ($\sim$ 20 ms), the *D* and *v* profiles are assumed to be constant in time, thus experimental plasma conditions are chosen to avoid transients such as ELMs. To study the sensitivity of this procedure, simulated data were generated by running STRAHL with the same transport coefficient profiles from Fig. 2(g-h) (solid lines) and adding Gaussian noise to the signal at a level comparable to the noise in the ME-SXR signals. The model was then run for a variety of other profiles, shown with the dashed lines in the same figure. In each case, the chi square of the fit of the model to the simulated data was computed. An initial attempt to fit the simulated 2D (radial and time) profiles did not converge to a unique D and v solution. The fits were dominated by the later stages of the gas-puff perturbation, when the impurity profiles approach a steady state. In a steady state, only the D/v ratio can be found. To rectify this problem, the chi square minimization can be performed at each time point independently. The contour plots in Fig. 4 show these resulting chi square values versus D and v for various time points following the gas puff. These figures reveal that for one time point, D and v cannot be independently determined. A dashed line highlights the set of possible solutions. However, as time evolves this line rotates about a fixed pivot, marked with an X, which represents the unique solution. Note that the perturbation only lasts $\sim$ 20 ms, and time resolution on the order of 1 ms is required to perform this measurement.

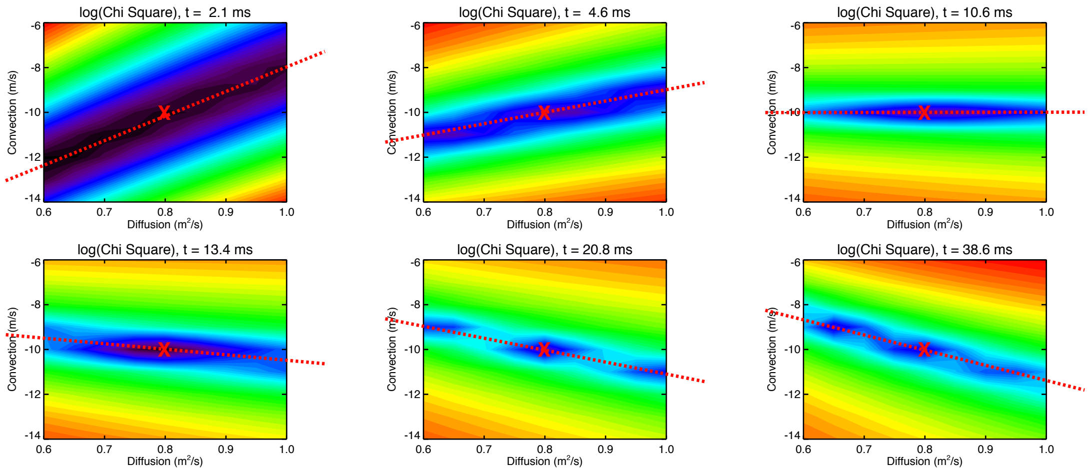

Figure 4: Chi square of model's fit to simulated data versus $D(r/a=1)$ and $v(r/a=1)$ for 6 time points. The X's mark the correct solution, used to generate the simulated data. The dashed lines highlight the set of D and v values that best match the simulated data at that time. The line rotates about the correct values as time evolves.

Experiments are planned with the full diagnostic to measure the effects of applied 3D fields on impurity transport, and a joint experiment will be conducted to simultaneously measure turbulence and multichannel transport for a variety of NSTX plasma conditions. Multiple impurity species will be used to obtain Z-scalings in each case.

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