Two-point modeling of SOL losses of HHFW power in NSTX

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Abstract

High-harmonic fast-wave (HHFW) heating is a heating and current-drive scheme on the National Spherical Torus eXperiment (NSTX) complimentary to neutral beam injection. Previous experiments suggest that a significant fraction, up to 50%, of the HHFW power is promptly lost to the scrape-off layer (SOL). Research indicates that the lost power reaches the divertor via wave propagation and is converted to a heat flux at the divertor through RF rectification rather than heating the SOL plasma at the midplane [1]. This counter-intuitive hypothesis is investigated using a simplified two-point model [2], relating plasma parameters at the divertor to those at the midplane. Taking measurements at the divertor region of NSTX as input, this two-point model is used to predict midplane parameters, using the predicted heat flux as an indicator of power input to the SOL. These predictions are compared to measurements at the midplane to evaluate the extent to which they are consistent with experiment.

Motivation

While ohmic heating is an effective heating and current-drive scheme, there is a fundamental limit on the temperatures it may produce. As such, for fusion devices, additional means of heating are required. Beam power has seen much success ansd widespread use amongst Tokamak devices, but it requires a substantial amount of the device wall to be dedicated to beam input/output. For reactor applications, this poses two important problems: it allows for the beam systems to be damaged by energetic neutron flux due to the lack of shielding and reduces the amount of wall space that may be dedicated to tritium breeding. Radio-frequency (RF) power may potentially be a solution that avoids these problems. That being said, it is not without problems of its own. An important challenge, particularly for ion-cyclotron and HHFW heating schemes, is the presence of significant power losses to the outer edges of the plasma. RF heating experiments performed on NSTX have exhibited significant power losses (up to 50%) in the SOL, producing a hot spiral extending into both the upper and lower divertor regions of the device. These spirals have been shown to be the footprint of the magnetic field lines passing in front of the RF antenna, including those within the SOL that do not connect to antenna itself.

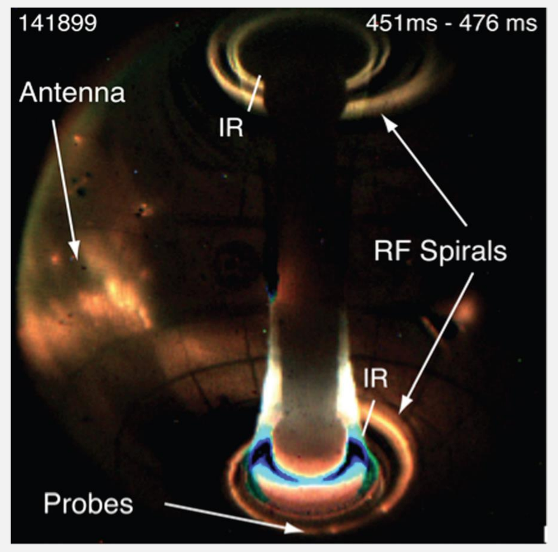


Figure 1: The picture shows a view from inside of the NSTX device during shot 141899. Labeled are the locations of the antenna, the RF spirals, the probe array, and the IR edge diagnostic. (Adapted from [1])

Previous research has indicated that, rather than heating the plasma immediately in front of the antenna, the lost power is converted directly to a heat flux at the divertor. This project is interested in providing further investigation into this hypothesis.

References

[1] R. J. Perkins et al., Phys. Plasmas 22 042506 (2015)

[2] P. C. Stangeby, The plasma boundary of magnetic fusion devices (Institute of Physics Publishing, Bristol, 2000).

Derivation of the Two-Point Model

The two-point model is designed to approximate the relationship between parameters at two points within the SOL, one upstream and one downstream. It operates on three basic principles: particle balance, pressure balance, and power balance. In order to simplify the situation, a number of important assumptions are made, allowing us to easily describe these principles mathematically.

Particle Balance Assumptions:

- Recycling neutrals are ionized in a thin layer just in front of the target and any neutrals resulting from the impact of an ion travelling along a particular field line are ionized along that same field line
- No cross-field diffusion and no flow velocity along the SOL, excepting the thin ionization region, where the particles accelerate from zero to the sheath entrance speed (c_s)
- No volume recombination (i.e. the target is the only particle sink)

$\Longrightarrow$ The particle balance is purely 1D

Pressure Balance Assumptions:

- No friction between plasma in the ionization region and the target and no viscous effects

$$\Longrightarrow \mathrm{p} + \mathrm{nm}v^2 = constant$$

- For $T_i = T_e$, we may rewrite the total pressure as:

$$p_{total} = p_{static} + p_{dynamic} = 2nkT + nmv^2$$

- Since the pressure is balanced, the upstream pressure equals the pressure at the target:

$$n_t(2kT_t + mv_t^2) = 2n_u kT_u$$

$$n_u T_u = 2n_t T_t \qquad (1)$$

Power Balance Assumptions:

- Since most of the SOL has no flow velocity, the parallel heat flux ($q_\parallel$) is carried entirely by conduction. If all of the heat flux is inputted at a point upstream a distance L from the target, then:

$$T_u^{7/2} = T_t^{7/2} + \frac{7}{2} q_\parallel \frac{L}{\kappa_{0e}} \qquad (2)$$

Here, the electron parallel conductivity coefficient is used, assuming that of the ions is comparatively small and that the electrons and ions are thermally coupled.

- Assuming that the temperature change over the ionization region is small, we may write the parallel heat flux as:

$$q_\parallel = q_t = \gamma n_t k T_t c_{st} \qquad (3)$$

While equations (1) – (3) form the basic two-point model, these equations can be modified to include correction factors that compensate for various types of energy and momentum losses otherwise not accounted for.

Shot 141899 Parameters

Applied HHFW power (P_{RF}): 1.3 MW
Applied NB power (P_{NB}): 2 MW
Toroidal field (B_T): 4.5 kG
Plasma Current (I_P): 1.0 MA
Magnetic Pitch (in SOL): ~39.6°
Gas: Deuterium

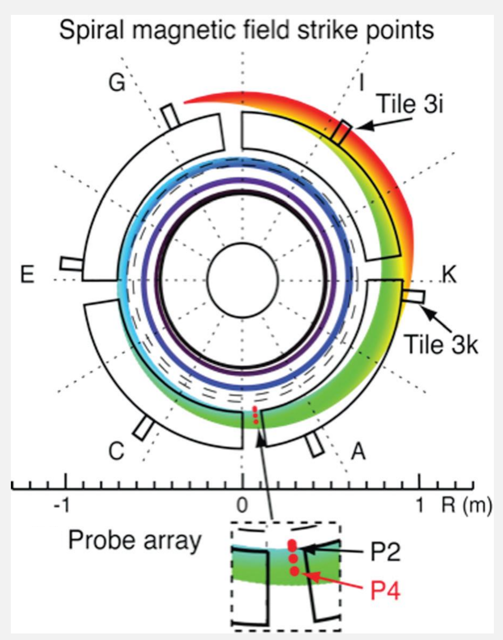


Figure 2: The diagram shows the location of the RF spiral, as well as the location of the divertor Langmuir probe array. (Adapted from [1])

Analysis of Triple Probe Data

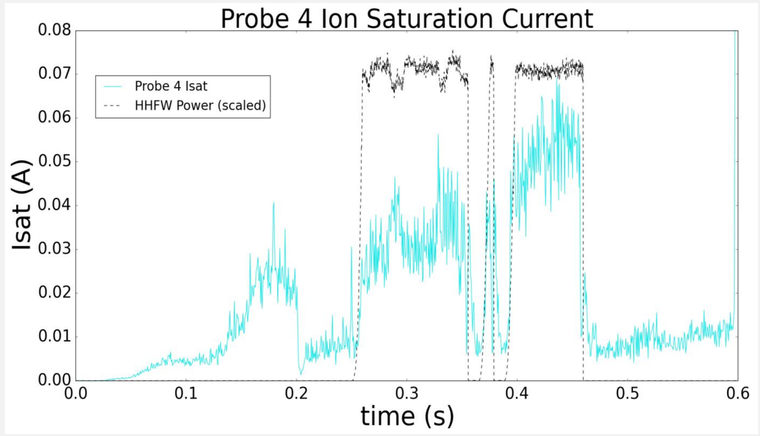


Figure 3a: The figure above depicts the smoothed Isat signal measured by probe 4 as a function of time, as well as a scaled HHFW power signal. Probe 4 is located at R = 70.03 cm, inside of the RF spiral. The signal of probe 4 shows anomalously high dependence of Isat on the presence of HHFW power. The data is smoothed by choosing the median of each 150 point block of 500 000 points.

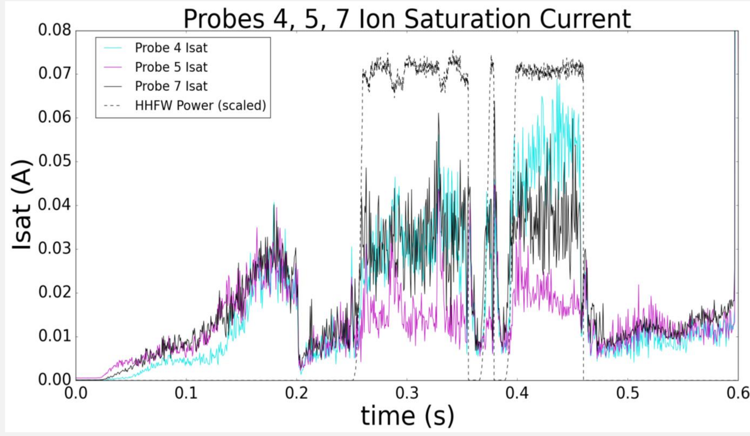


Figure 3b: The figure above depicts the smoothed Isat signals measured by probe 4 and its two closest neighbors, probes 5 and 7, located at R = 71.15 cm and 68.33 cm, respectively. All three probes are located inside of the RF spiral. The data is smoothed using the same method as figure 3a.

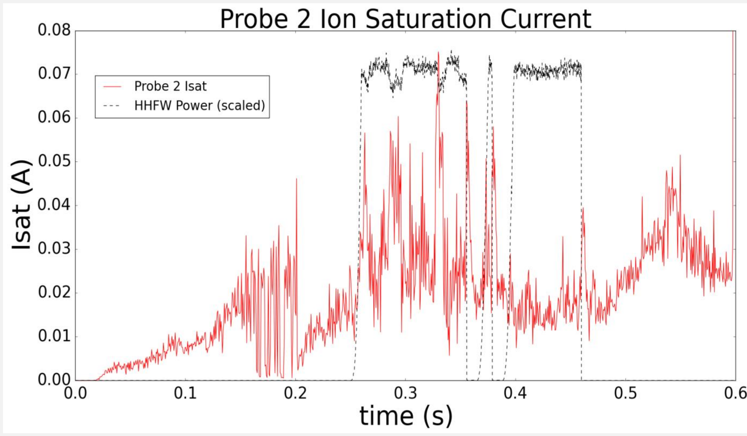
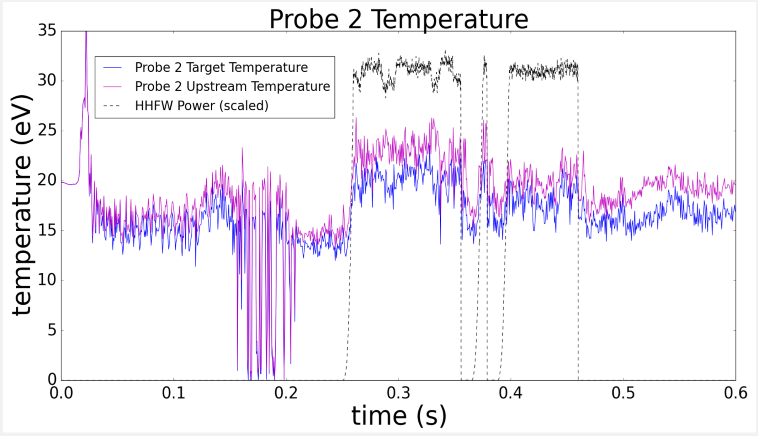
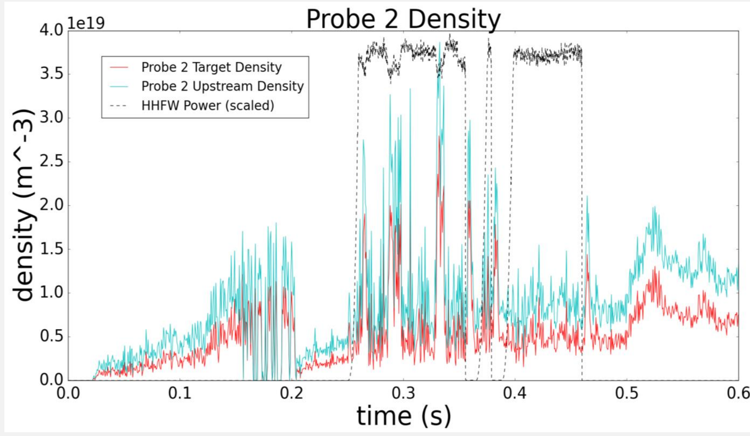
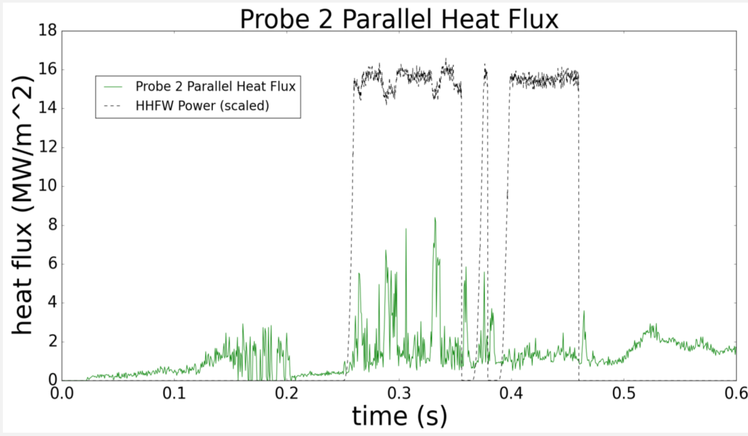


Figure 3c: The figure above depicts the smoothed Isat signal measured by probe 2, located at R = 65.23 cm, outside the RF spiral. While probe 2 shows heavy influence from the ELM and arc that occur during the first half of the HHFW pulse, it shows little to no dependence on the presence of the HHFW power itself, supporting the conclusion that the HHFW power is being confined to the RF spiral. Smoothing mehtod identical to figure 3a,b.

Application of the Two-point Model

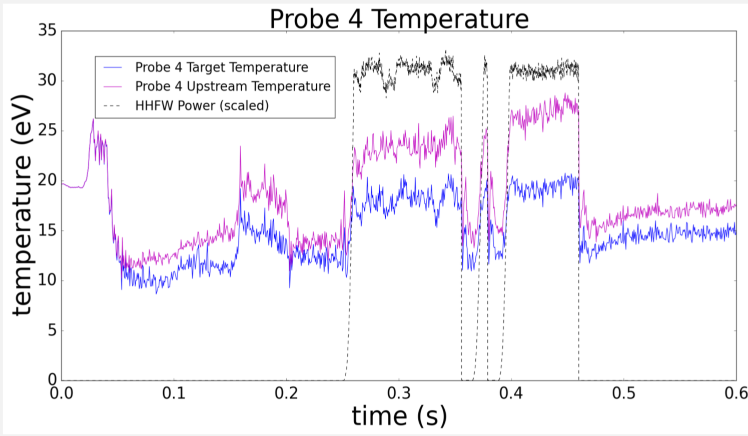


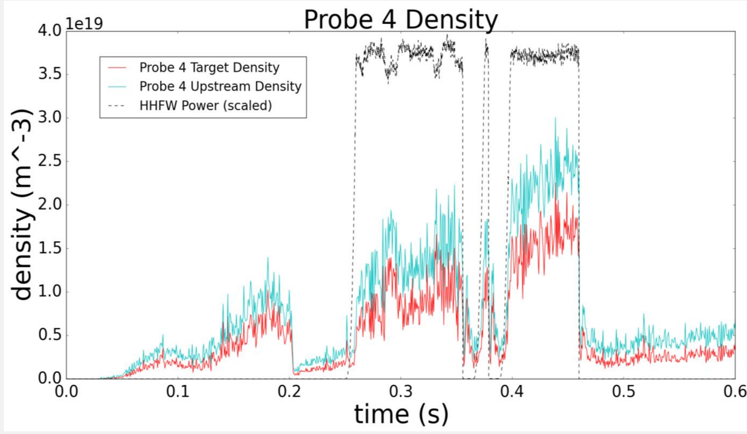


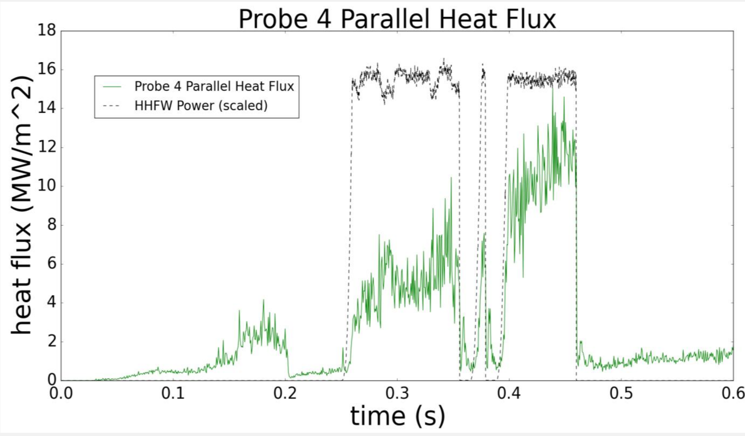


Taking triple probe measurements from the divertor as input, the original two-point equations were rearranged to allow for the prediction of upstream quantities. The surrounding plots show the results predicted by the model. These results display a number of interesting features. At the most general level, it can be seen that the upstream quantities experience systematically greater dependence on the applied RF power. This observation is quantified in the table below. The fact that the density, rather than the temperature, at probe 4 sees significantly greater dependence on RF power, may suggest that the anomalous behavior of the ion saturation current is linked to this surge in density, as opposed to other factors. Additionally, it would appear that an increasing parallel temperature and density gradient is formed within the spiral as RF power is applied.

Change Factors for HHFW Power Jumps	t = 0.25s	t = 0.34s	t = 0.40s	t = 0.46s
Tt4	1.42	0.73	1.45	0.77
Tu4	1.58	0.69	1.65	0.65
Nt4	3.71	0.38	4.02	0.21
nu4	3.61	0.39	3.87	0.24
Tt2	1.42	0.79	1.17	0.91
Tu2	1.45	0.82	1.09	0.99
nt2	2.18	0.82	0.64	1.79
nu2	2.21	0.79	0.73	1.60







Data Analysis Process

1. Triple Probe Data → 2. Analysis Scripts (n_t, T_t) → 3. Two-point Model ($n_u, T_u, q_\parallel$) → 4. Visualization and Post-Processing

Acknowledgements

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