Utilization of Two-Point Model to Estimate Separatrix Temperature in NSTX

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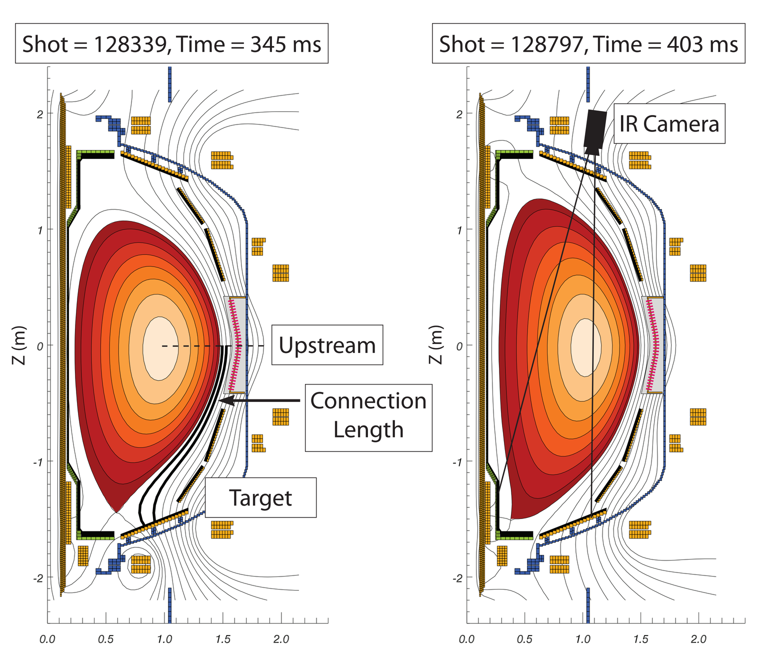
Motivation

A flat temperature profile in the core plasma is generally desired for peak plasma performance and stability. Therefore, it is useful to know the separatrix temperature as a point of comparison to the core temperature. However, current methods of estimating the separatrix temperature have no means of pin-pointing the exact location of the separatrix and are not entirely accurate.

The method being discussed utilizes a simple two-point model of the scrape-off layer (SOL) to theoretically predict the separatrix temperature based on other measured quantities. The two points refer to the upstream location at the midplane and the downstream position at the target.

Scrape-Off Layer

Once particles are transported across the separatrix, they enter the scrape-off layer and stream along the field lines to the limiting surface. During the traverse to the divertor, the particles can lose or transfer energy in several ways. Physically complete modelling is available in the form of 2D edge codes, however these codes are computationaly expensive and cannot incorporate all of the experimental data available.

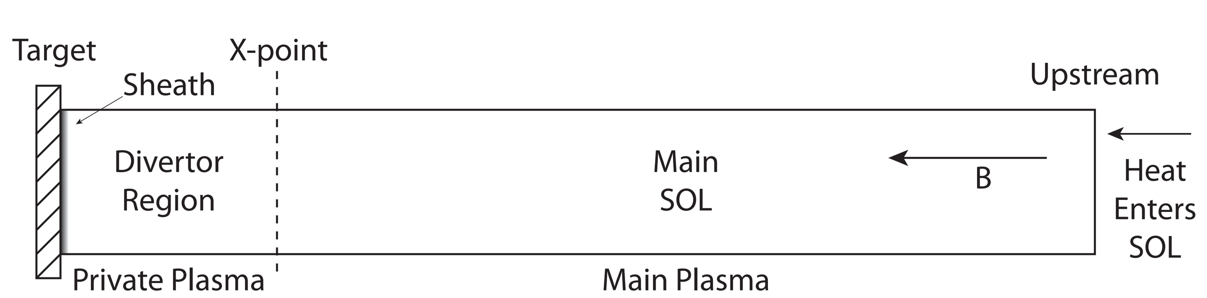


Assumptions

- All heat enters at midplane
- Particles remain in flux tubes
- Validity of two-point model can be improved by including correction terms

Losses

- Charge exchange
- Ionization
- Recombination
- Radiation
- Recycling
- Free-streaming electrons



References:

[1] Stangeby, P. C. (2000). The Plasma Boundary of Magnetic Fusion Devices. Institute of Physics. Bristol.

[2] Pitcher, C. S. and Stangeby, P. C. (1997). Experimental divertor physics. Plasma Physics and Controlled Fusion, 39: 779-930.

[3] Fundamenski, W. (2005). Parallel heat flux limits in the tokamak scrape-off layer. Plasma Physics and Controlled Fusion, 47: R163-R208.

[4] Ahn, J.-W. et al. (2008). The role of parallel heat transport in the relation between upstream scrape-off later widths and target heat flux width in h-mode plasmas of the national spherical torus experiment. Physics of Plasmas, 15.

Two-Point Model Equations

The general form of the two-point model was adapted from Stangeby.[1]

The first equation comes from the continuity and momentum equations assuming one-dimensional, steady-state, inviscid flow without any other body forces. If some loss of momentum between the upstream point and the target is allowed, the term f_{mom} is introduced as in equation (1).

$$\frac{\partial n}{\partial t} + \nabla\cdot(n\mathbf{v}) = S$$

$$\rho\left(\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v}\cdot\nabla)\mathbf{v}\right) = -\nabla p - m\mathbf{v}S + \mu\nabla^2\mathbf{v} + f \qquad \boxed{f_{mom} n_u T_u = 2 n_t T_t} \quad (1)$$

The second equation comes from integrating the conduction equation from the midplane to the target along the magnetic field. In order to account for heat carried through convection, the term f_{cond} is included to represent the percentage of the heat carried through conduction.

$$q_{\parallel,cond} = -\hat{\kappa}_{0,e} T^{5/2}\frac{dT}{ds_\parallel}$$

$$\int_0^{L_c} ds_\parallel \left[f_{cond} q_\parallel = -\hat{\kappa}_{0,e} T^{5/2}\frac{dT}{ds_\parallel}\right] \qquad \boxed{T_u^{7/2} = T_t^{7/2} + \frac{7}{2}\frac{f_{cond} q_\parallel L_c}{\hat{\kappa}_{0,e}}} \quad (2)$$

The last equation comes from power balance into and out of the sheath region near the divertor. In order to account for power lost in the divertor region, the term f_p is included as in equation (3). This term includes losses from both recycling and impurity radiation.

$$q_{sheath} = q_\parallel - q_{rad}^{SOL} - q_{rcy} = \gamma n_t k T_t c_{st}$$

$$q_\parallel = \left(1 + \frac{q_{rad}^{SOL} + q_{rcy}}{\gamma n_t k T_t c_{st}}\right)\gamma n_t k T_t c_{st} \qquad \boxed{q_\parallel = f_p \gamma n_t k T_t c_{st}} \quad (3)$$

$$f_p \equiv 1 + \frac{q_{rad}^{SOL} + q_{rcy}}{\gamma n_t k T_t c_{st}}$$

Correction Terms

To include the effects from the loss mechanisms, four correction terms were introduced.

1. Kinetic Correction

Because the SOL is typically in a range of intermediate collisionality, some portion of the heat is carried by free-streaming electrons. Including this alternate path for the heat flux as presented by Fundamenski[3], the conduction equation used in deriving equation (2) becomes:

$$\frac{dT}{ds_\parallel} = -\left(\kappa_0 T^{5/2}\left(q_\parallel^{-1} - q_{e,limit}^{-1}\right)\right)^{-1}$$

$$q_{e,limit} = \alpha_e n v_{te} k T_e \qquad \alpha_e \approx 0.15$$

$$\hat{\kappa}_{0,e} = \kappa_{0,e}\left(1 - \frac{q_\parallel}{q_{e,limit}}\right)$$

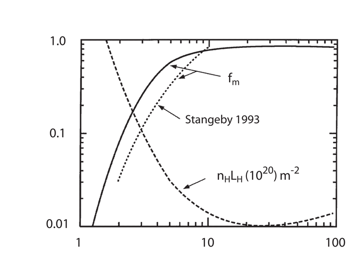
2. Convection Correction

Some of the heat entering the SOL will be carried to the wall via convection. Therefore, the model includes a fixed parameter that represents the amount of heat carried through conduction.

$$f_{cond} = 0.8$$

3. Momentum Correction

Because the particles will collide along the path to the divertor, there will be some momentum loss. The form for this parameter was taken from Pitcher and Stangeby[2].



$$f_m = 10^{-2+1.961\tanh\left(2.347\log_{10}(T_t/1.3)\right)}$$

4. Power Correction

Lastly, some of the power is lost in the divertor region due to effects such as impurity radiation and recycling. This model assumes the following forms for these losses.

$$q_{rcy} = \epsilon\Gamma_t \qquad \epsilon \approx 25\text{ eV}$$

$$q_{rad}^{SOL} = f_{imp} n_i^2 c_{rad}\frac{L_c}{3} \qquad f_{imp} \approx 5\%$$

$$f_p = 1 + \frac{\epsilon/\gamma}{T_t} + \frac{f_{imp} n_i c_{rad} L}{3\gamma e T_t c_{st}}$$

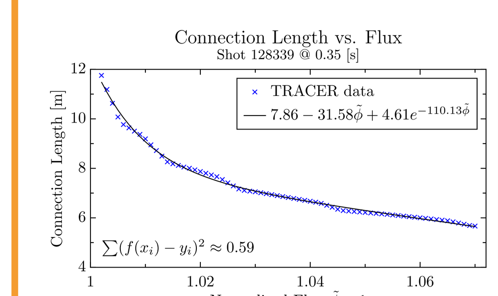
Inputs

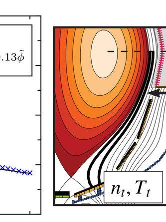
In order to most accurately model the NSTX shot under consideration, experimental data is used as an input whenever possible. For a given shot, the following items are used as inputs to the model:

- Connection Length, L_c
- Upstream density, n_u
- Neutral beam power, P_{NBI}
- Heat flux e-folding length, λ_q

1. Connection Length

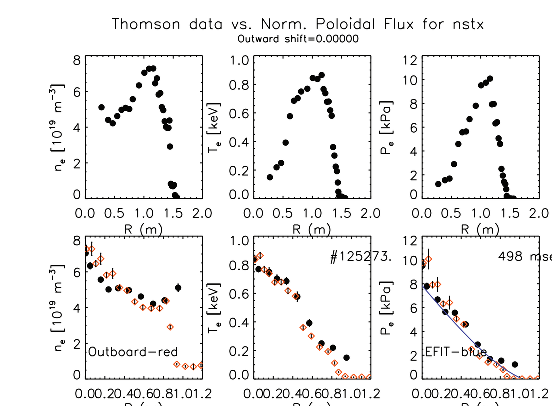
The connection length, or distance along the field line from the midplane to the divertor, is one of the primary inputs to the TPM. This quantity was found from the magnetic reconstruction of the particular shot with the TRACER code.





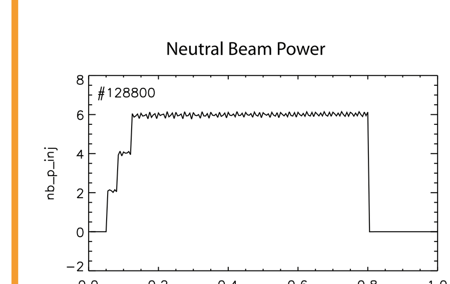
2. Upstream Density

The upstream density is estimated from the Thomson profile.



3. Neutral Beam Power

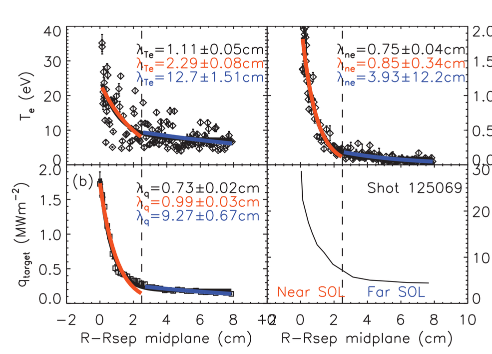
The power into the SOL is computed from the experimental power at a given point in time.



4. Heat Flux e-Folding Length

In order to match the experimental cross-field transport, λ_q is calculated from IR camera data as described in Ahn et al[4]. This value is then used in conjunction with the NBI power to compute $\chi_\perp$.

$$\chi_\perp = \frac{\left(\frac{7^5\lambda_q^9}{8^5\pi^{12}}\left(\frac{P_{sol}^5\kappa_{0,e}^2(B_P/B_T)^2}{L^2R^5r^7}\right)\right)^{1/7}}{en_u}$$



Taken from Ahn et al.[4]

Code

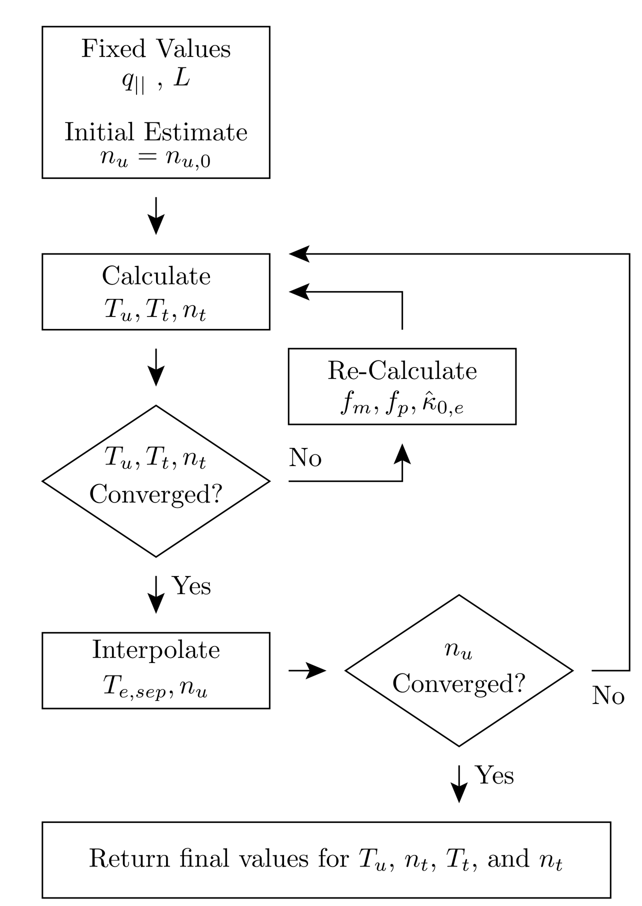
The TPM equations can be solved analytically for constant loss terms. Because of the functional dependence of three of the loss terms, the model implements an under-relaxation iterative technique. This technique calculates the loss parameters using the values from the previous iteration.

The result is set of nested loops that repeat until the desired accuracy is obtained.

$$c_1 = \frac{7}{2}\frac{f_c q_\parallel L}{\hat{\kappa}_{0,e}}$$

$$c_2 = \left(\frac{2q_\parallel^2 m_i}{f_p^2 f_m^2 n_u^2\gamma^2 e^3}\right)^{7/4} \qquad \boxed{x^3 + c_1 x - c_2 = 0}$$

$$x = T_t^{7/4}$$

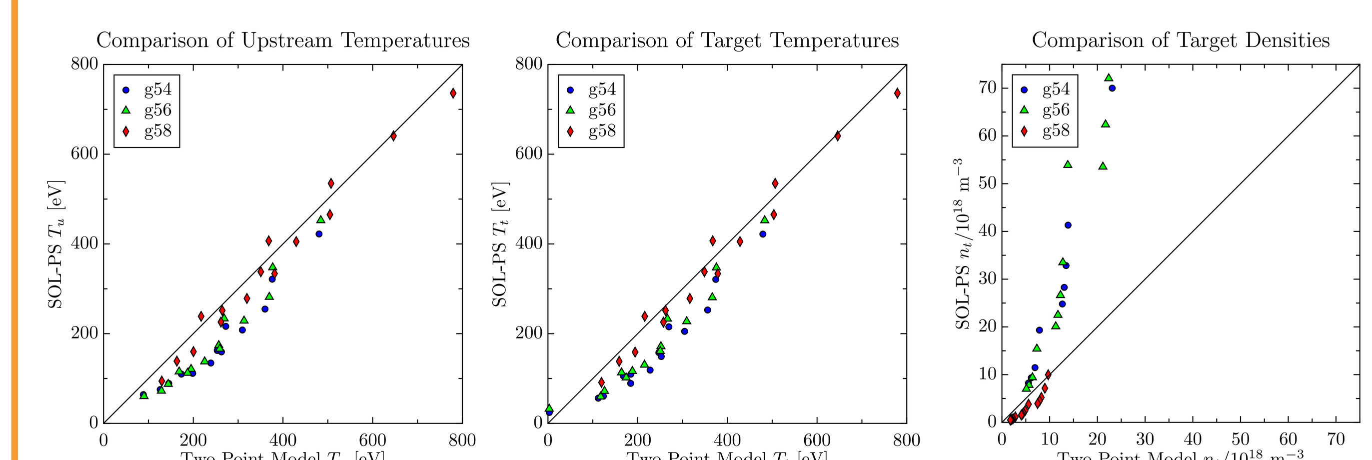


Results

Comparing to simulated runs from SOL-PS, there was remarkably good agreement on the upstream and target temperatures. The target density did not agree well; however this could be due to the effect of the neutral background present in SOL-PS. More work needs to be done to firmly establish the regimes where the model is not accurate.

Discharge: g58 jetlike DN Flux value: 1.01					Two-point model		
$q_\parallel$	n_u	T_u	$T_{u,tpm}$	n_t	$n_{t,tpm}$	T_t	$T_{t,tpm}$
150.4900	1.95e+019	94.2662	129.7726	9.98e+018	9.70e+018	91.3129	119.3521
231.7500	1.06e+019	251.7276	264.5513	2.48e+018	4.87e+018	251.6930	262.1068
182.2000	5.08e+018	406.8468	368.2408	7.83e+017	2.33e+018	406.9155	367.4082
385.2600	1.78e+019	225.8844	261.6326	5.23e+018	8.26e+018	225.6040	257.4128
419.7800	9.30e+018	405.2379	429.5042	1.71e+018	4.27e+018	405.2997	428.1984
344.0700	4.15e+018	640.8234	646.4224	5.48e+017	1.90e+018	640.8554	646.0349
614.4300	1.62e+019	333.7918	381.2087	3.94e+018	7.47e+018	333.7441	378.6203

Table 1: Comparison of results from SOL-PS and Two-point model.



Using NSTX experimental discharges as input to the TPM, the separatrix temperature compared well to that calculated by the 2D codes for the same shot.

	Two-point Model					2D Codes			
Shot	T_{sep}	$n_{e,sep}$	T_t	$n_{e,t}$		T_{sep}	$n_{e,sep}$	T_t	$n_{e,t}$
128339	42.36	1.68e19	3.90	3.43e19		39.13	7.01e18	—	—
128797	160.66	3.32e19	117.35	1.64e19	⟶	97.27	3.17e19	11.84	3.00e20
128800	67.95	3.59e19	3.41	1.01e20		59.16	3.66e19	5.96	1.79e20

Table 2: Comparison of reported temperatures and densities between two-point model and UEDGE/SOL-PS.

Conclusions

The employed method seems to work reasonably well under some conditions as an indicator of the separatrix temperature.

The results from experimental data indicate a separatrix temperature of around 40 to 60 eV in agreement with 2D edge codes.

This method does seem to have some difficulting in obtaining the detached and high-recycling regimes when using realistic heat fluences.

Future Work

Determine why the high-recycling regime cannot be matched. Then compare results from the TPM to a wider range of discharges to examine the applicability of the model.

Possibly expand into a more sophisticated multi-point model that could potentially include more effects directly. Such a model could include a neutral population that undergoes charge-exchange, ionization and recombination.

Examine how the separatrix temperature changes with scans in recycling, core density, SOL width, etc.