Electron thermal diffusivity differences due to magnetic geometry on the HSX stellarator

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Motivation

Experimentally investigate thermal transport on the Helically Symmetric eXperiment (HSX), a Quasi-Helically Symmetric (QHS) stellarator

- HSX has considerable magnetic geometry flexibility owing to a set of auxiliary coils surrounding its main field coils
- A Thomson Scattering system collects electron temperature and density profiles passively throughout experimental runs
- Changes in diffusive heat flux can be observed by the Thomson system when the magnetic geometry is altered
- An enhancement in heat flux has been measured when magnetic well depth is decreased by adding toroidal flux

Diffusive Heat Flux Model

Electron temperature T_e and density n_e profiles are required to calculate an experimental electron thermal diffusivity χ_e profile. The HSX Thomson system provides:

- T_e, n_e at 10 spatial points over radius
- n_e obtained from signal intensity
- T_e obtained by Maximum Likelihood
- 6 individual discharges ensembled

Start with energy conservation for electrons:

$$\frac{\partial}{\partial t}\left[\frac{3}{2}n_e T_e\right] + \nabla\cdot\mathbf{q}_e = p_{abs} - p_{loss} = p_{net}$$

Make the following assumptions:

- Plasma has reached a steady state
- Heat flux is diffusive $\mathbf{q}_e = n_e\chi_e\nabla T_e$ within $0.1 < r/a < 0.6$
- Absorbed power density is dominated by ECRH source
- Absorbed power density far exceeds losses $p_{abs} >> p_{loss}$

Energy conservation becomes:

$$\nabla\cdot\mathbf{q}_e = p_{abs} = p_0\left[1-(r/a)^2\right]^{p_1}$$

where p_0 is used to scale to absorbed power measured by diamagnetic loop at turn-off, p_1 used to fit profile shape from raytracing.

Finally integrating over plasma volume yields:

$$q_e = \frac{1}{r}\int_0^r p_{abs} r' dr'$$

$$\chi_e = \frac{q_e}{n_e \nabla T_e}$$

Gaussian Process Regression (GPR) Method

If n_e and ∇T_e profiles can be determined from Thomson data, χ_e can be directly calculated. GPR provides:

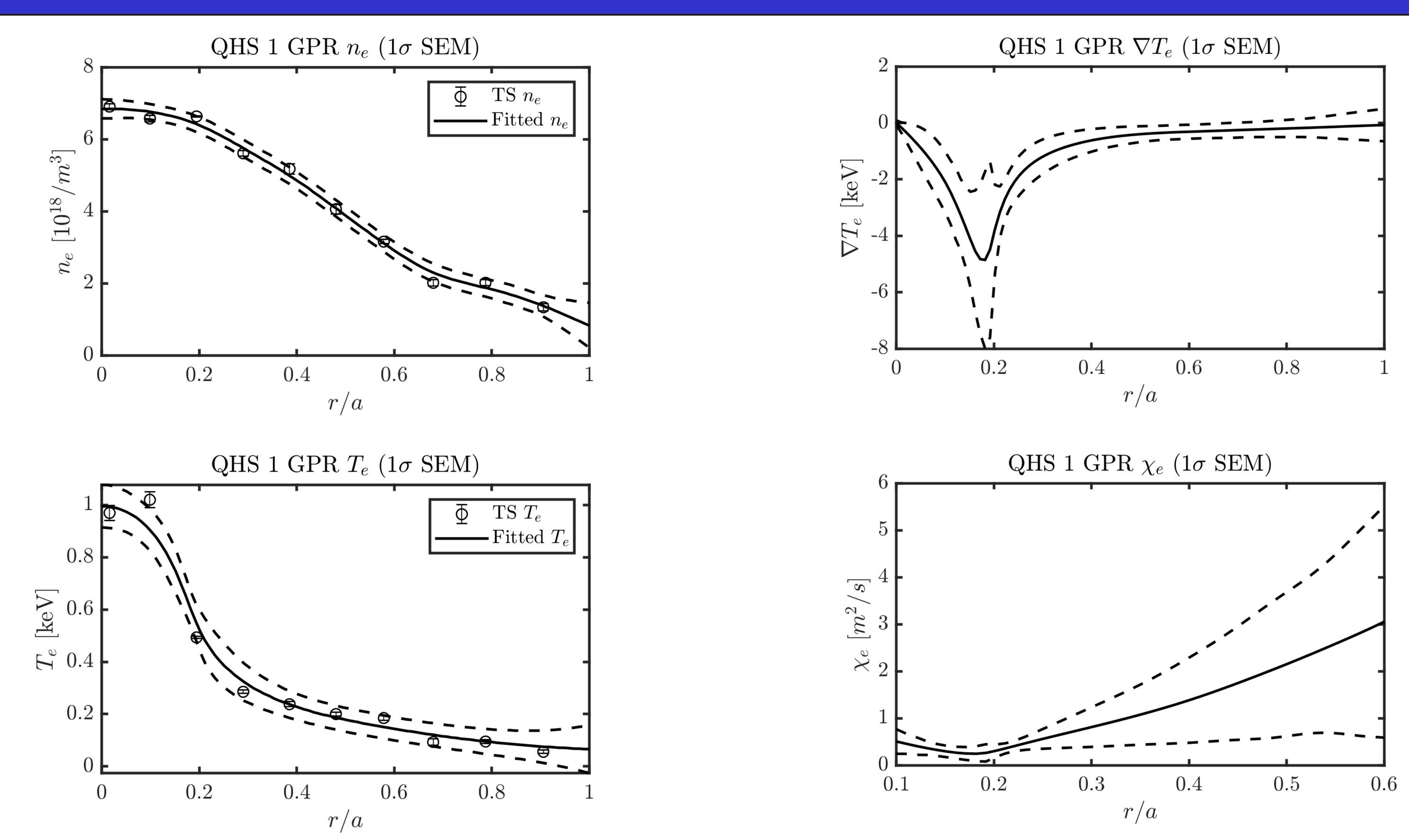
- Non-parametric smooth curve fitting
- Gradient fit constraints and predictions
- Bayesian-probability based method

GPTools library V0.2.3 [1] used for fitting,

- n_e fit = SE kernel + linear mean + diagonal noise
- T_e fit = SE kernel + hyperbolic tangent mean + diagonal noise

Problem - expanding uncertainty caused by singularity in error propagation as $\nabla T_e \to 0$:

$$\sigma_{\chi_e} = \chi_e\sqrt{\left(\frac{\sigma_{n_e}}{n_e}\right)^2 + \left(\frac{\sigma_{\nabla T_e}}{\nabla T_e}\right)^2 + \left(\frac{\sigma_{q_e}}{q_e}\right)^2}$$



Least Squares (LSQ) Regression Method

To avoid calculating ∇T_e directly, instead use an assumed form for χ_e [2]:

$$\chi_e = \chi_0 + \chi_1 r + \chi_2 r^2$$

then calculate a modeled T_{mdl} which can be fit to T_e measurements by nonlinear Least Squares:

$$T_{mdl} = \int_0^r \frac{\partial T_e}{\partial r'}dr' + T_{peak}(r=0)$$

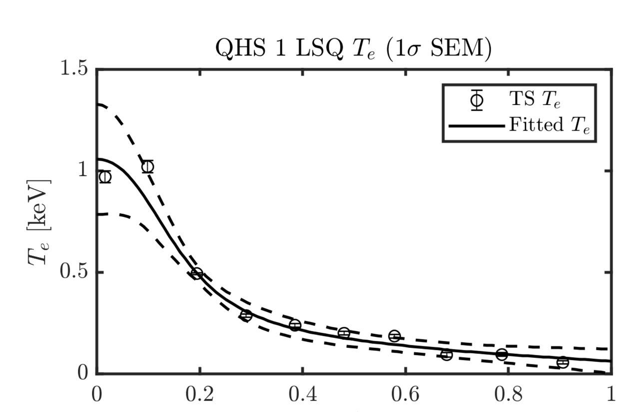
$$F_i = \left(T_e(r_i) - T_{mdl}(r_i)\Big|_{\mathbf{X}}\right)\frac{1}{\sigma_{T_e}(\rho_i)}$$

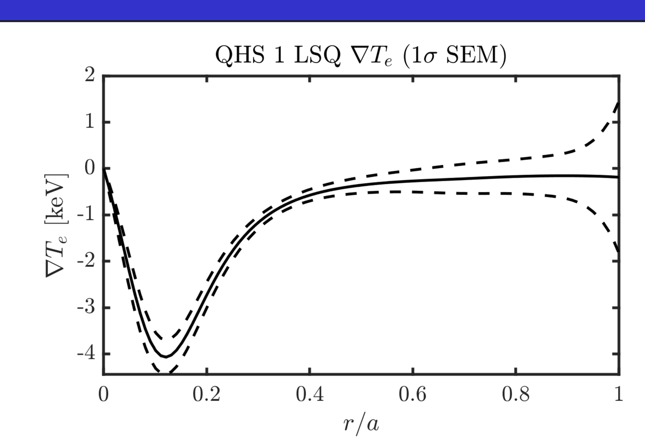
$$\mathbf{X} = [T_{peak}, \chi_0, \chi_1, \chi_2]$$

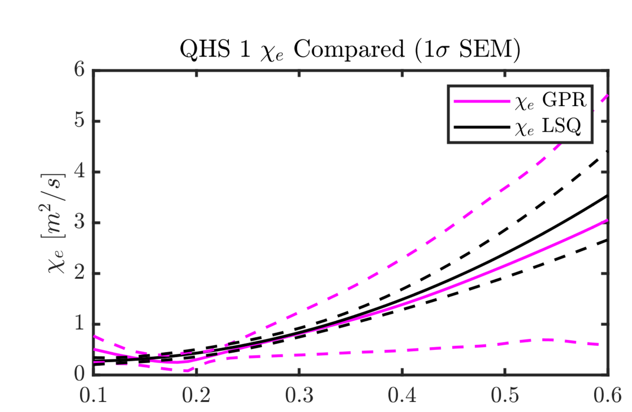
Uncertainty in χ_e is then determined based upon minimization parameters via covariance matrix, calculated using weighted Jacobian and Mean Squared Error (MSE):

$$\mathbf{Cov} = inv(\mathbf{J}' * \mathbf{J}) * MSE$$

$$\sigma^2_{\chi_e} = \chi_e^2\left(\left(\frac{\sigma_{n_e}}{n_e}\right)^2 + \left(\frac{\sigma_{q_e}}{q_e}\right)^2\right) + \mathbf{Cov} * \mathbf{r}^T\mathbf{r}$$







HSX Magnetic Configurations

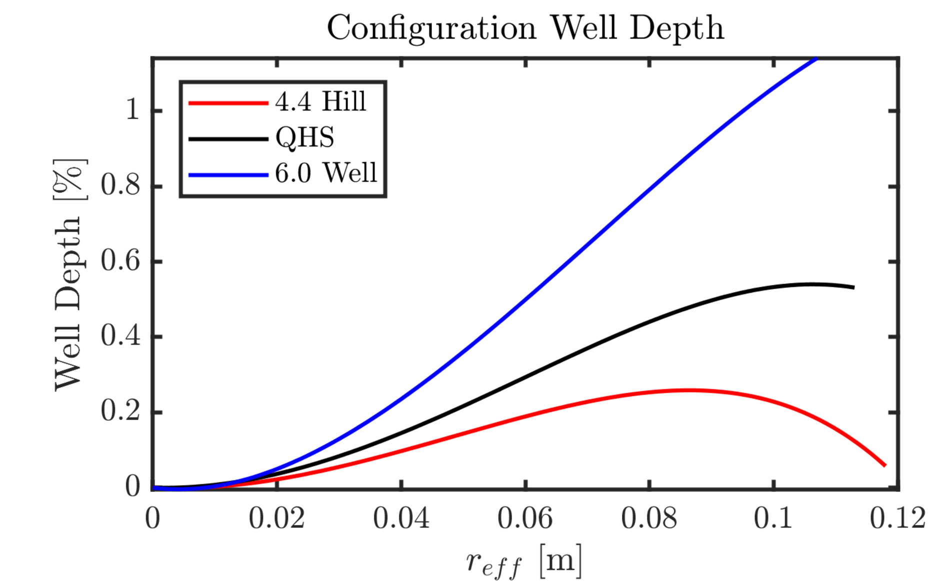
For toroidal flux Ψ and volume V, relative well depth W_D is:

$$W_D = \frac{\frac{dV}{d\Psi}\left(\frac{r}{a}=0\right) - \frac{dV}{d\Psi}}{\frac{dV}{d\Psi}\left(\frac{r}{a}=0\right)}$$

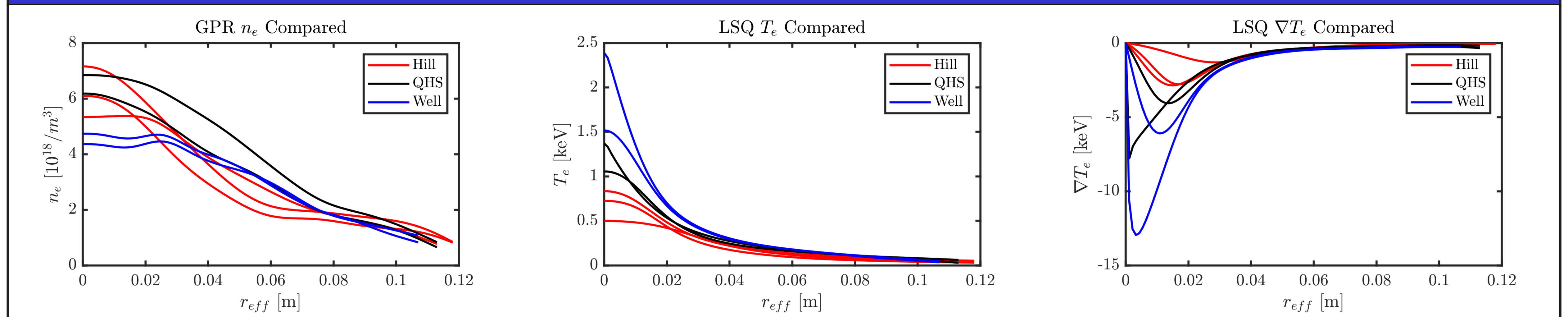
Hill - QHS - Well Configuration range of HSX geometry:

- Hill - increased Ψ, decreased W_D, increased plasma radius
- QHS - neoclassically optimized geometry
- Well - decreased Ψ, increased W_D, decreased plasma radius

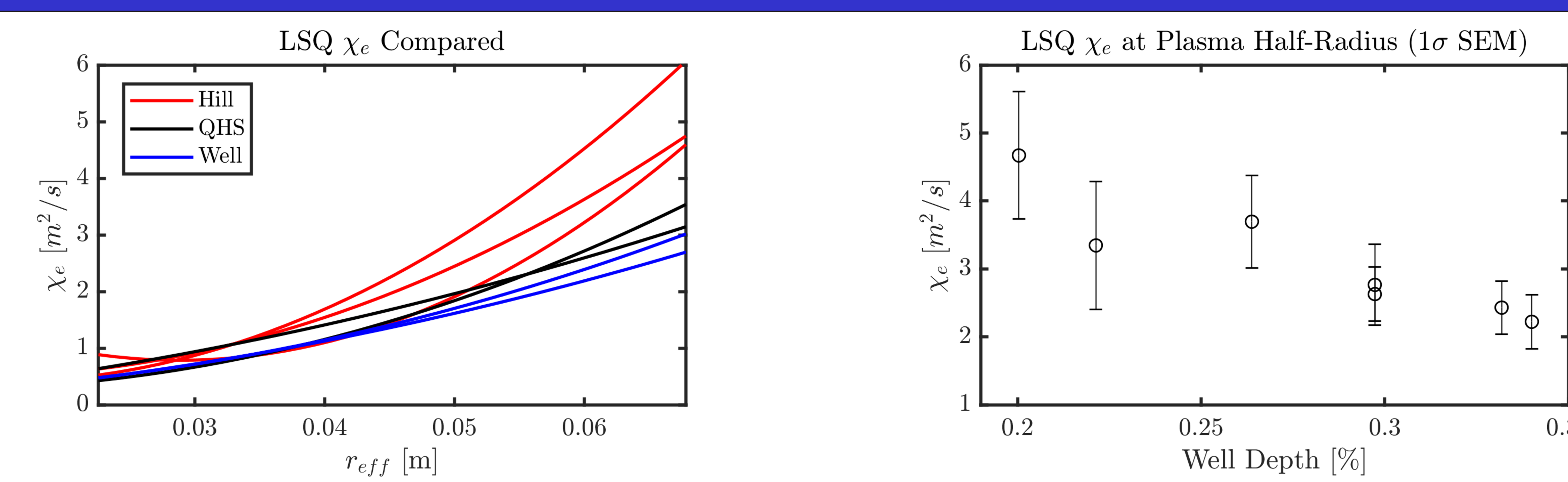
Configurations labeled by auxiliary coil current fraction.



Fits Used for Final Results



Diffusivity Results



Experimental χ_e Trend: Hill (small W_D) > QHS > Well (large W_D)

Summary & Future Work

Summary:

- A TS system has been used to make electron density and temperature measurements over a range of magnetic geometries
- These n_e and T_e profiles have been used to calculate electron thermal diffusivity using a diffusive energy flux model
- An enhanced diffusivity with decreasing magnetic well may suggest increased turbulent transport in those configurations

Future Work:

- Modeling will be performed to attempt to separate turbulence from neoclassical transport
- The mechanism primarily responsible for changing transport with respect to magnetic well will be identified
- The TS system will be upgraded to improve signal digitization and analysis techniques

References

[1] M. A. Chilenski, M. Greenwald, Y. Marzouk, N. T. Howard, A. E. White, J. E. Rice, and J. R. Walk. Improved profile fitting and quantification of uncertainty in experimental measurements of impurity transport coefficients using Gaussian process regression. *Nuclear Fusion*, 55(2):23012, 2015.

[2] H. Maassberg, R. Burhenn, U. Gasparino, G. Kühner, H. Ringler, and K. S. Dyabilin. Experimental and neoclassical electron heat transport in the LMFP regime for the stellarators W7-A, L-2, and W7-AS. *Physics of Fluids B*, 1993.

Contact & Acknowledgements

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Supported by DOE grant DE-FG02-93ER54222.