Modulated Heating Experiments on the HSX Stellarator

G.M. Weir, K.M. Likin, B.J. Faber[1], N. Marushchenko[2], Y. Turkin[2], J.N. Talmadge, D.T. Anderson,

HSX Plasma Laboratory, Univ. of Wisconsin, Madison, WI, USA, [1]Princeton Plasma Physics Laboratory, Princeton, NJ, USA, [2]Max-Planck-Institut fur Plasmaphysik, EURATOM Association, Teilinstitut Greifswald, Germany

Abstract

HSX (Helically Symmetric eXperiment) is a helical axis four field-period quasi-helically symmetric stellarator. A second 200 kW / 28 GHz ECRH system has been installed and tested, doubling the heating capacity of HSX and allowing modulated heating experiments.

- Modulated heating experiments with a new ECRH system on the HSX stellarator are used to determine the electron thermal diffusivity from the dynamic response of the electron temperature using the Electron Cyclotron Emission (ECE) diagnostic.
- The new ECRH system has a poloidally steerable mirror that is capable of depositing energy across the minor radius and refraction of the heating beam leads to differences in the width of the absorbed power profile compared to the primary ECRH system.
- The electron temperature is determined from the optically gray ECE by including finite reflectivity and optical depth and iterating the optical depth to a self-consistent electron temperature profile.
- Initial measurements yield an incremental thermal diffusivity consistent with the power-balance value in the core of HSX in-line with other stellarator results.

Heat Transport and Modulated Heating

- In modulated heating experiments the phase (φ) delay and amplitude (A) decay of electron temperature perturbations are independently related to the perturbed heat flux, and may be related to the experimental thermal diffusivity from Fourier's law, $q_e = -n_e\chi_e\nabla T_e$, in a cylindrical geometry ($r_n^{-1} = -[\ln n_e]'$) as

$$\chi_e^{inc} = \sqrt{\chi_e^A \chi_e^\varphi} = \frac{3}{4}\frac{\omega_{mod}}{-\varphi'[(\ln A)' + (2r)^{-1} - (2r_n)^{-1}]},\quad \text{where}\quad \chi_e^A = \frac{3}{4}\frac{\omega_{mod}}{[(\ln A)' + (2r)^{-1} - (2r_n)^{-1}]^2}\quad \text{and}\quad \chi_e^\varphi = \frac{3}{4}\frac{\omega_{mod}}{\varphi'^2}.$$

Due to damping, $\chi_e^\varphi \geq \chi_e^A$, but this effect cancels as modulation frequency increases and both converge independently towards χ_e^{HP}.

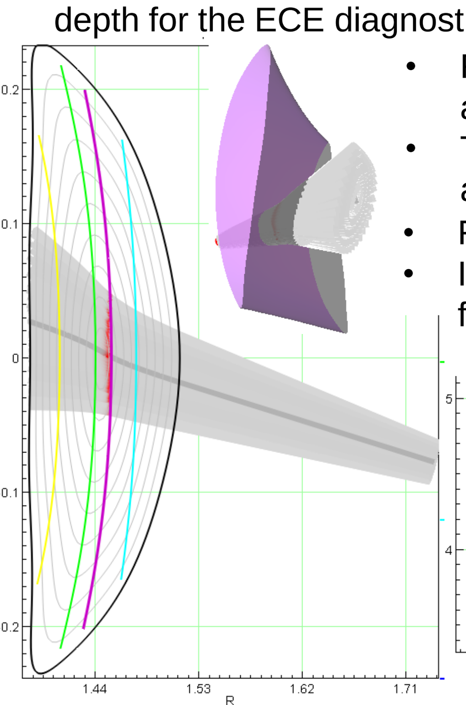
- The Trapped Electron Mode (TEM) has been shown to be linearly unstable in HSX [2], and a critical gradient in the electron temperature which agreed with that from linear gyrokinetic simulations of TEM turbulence has been observed on the ASDEX Upgrade tokamak [3].
- Knowledge of the incremental and power balance values allows the experimental critical gradient to be determined and compared with theory,

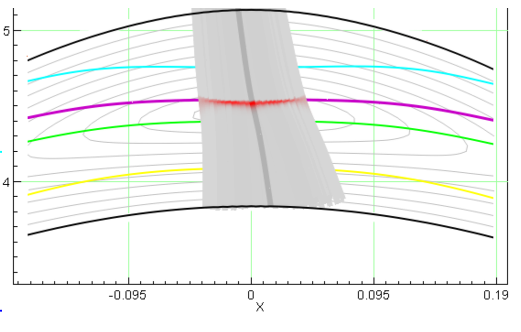
$$\chi_e^{inc} = \chi_e^{PB} + \frac{\partial\chi_e}{\partial(\nabla T_e)}\nabla T_{e,o} \to \left(\frac{R}{L_{T_e}}\right)_{crit} = \left(\frac{R}{L_{T_e}}\right)\frac{\chi_e^{inc} - \chi_e^{PB}}{\chi_e^{inc}}\quad \text{with}\quad \chi_e^{PB} = -\frac{q_{e,o}}{n_e\nabla T_{e,o}}.$$

- In tokamaks, the incremental value has been extensively observed to be greater than twice the power balance value, $\chi_e^{inc}/\chi_e^{PB} > 2$, while in stellarators they are approximately equal, $\chi_e^{inc} \approx \chi_e^{PB}$. HSX is in a unique position to study turbulent electron thermal transport as it has been optimized for neoclassical transport that typically dominates stellarator experiments.

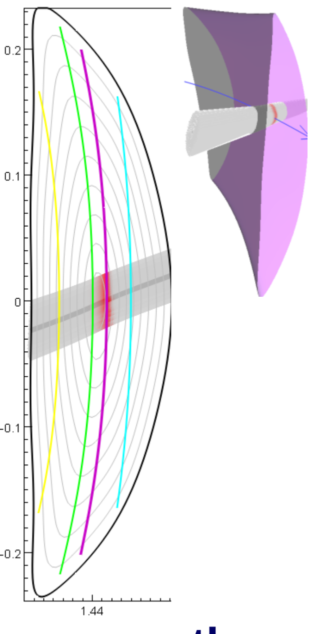
Ray Tracing Calculations: TRAcing VISualized[2]

- TRAVIS[2] is a ray tracing code developed for electron cyclotron studies in 3D magnetic configurations. [1]
- The code applies the geometric optics approximation to discretized microwave beams to determine the ray path and calculates the linear microwave absorption and associated optical depth along each ray.
- TRAVIS[2] is used to calculate the power deposition profile from two ECRH systems as well as the optical depth for the ECE diagnostic on HSX.





- Ray trajectories for the central channel of the ECE diagnostic are shown at right.
- The LCFS is shaded purple, the magnetic axis is in blue, and absorption is in red.
- Ray trajectories for the 2nd ECRH system are shown at left.
- In both calculations the beam diverges preferentially away from the density gradient.



Electron Cyclotron Emission

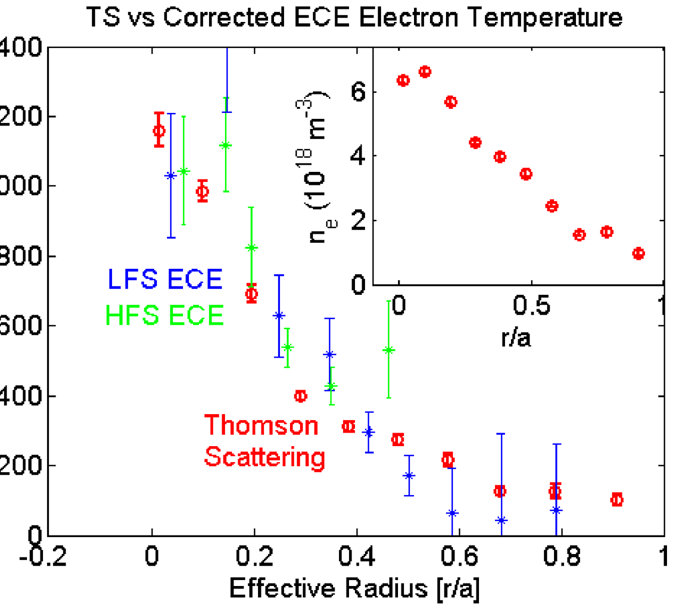
ECE Modeling

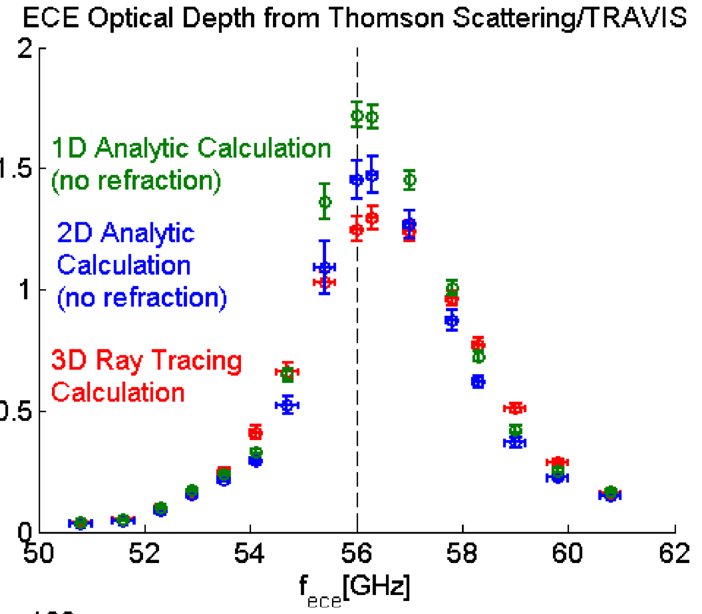
- ECE is governed by the radiation transfer equation, whose solution in a slab geometry in the limit of reflective parallel planes is:

$$T_{r,\omega} = T_e\frac{1 - e^{-\tau}}{1 - \rho e^{-\tau}},$$

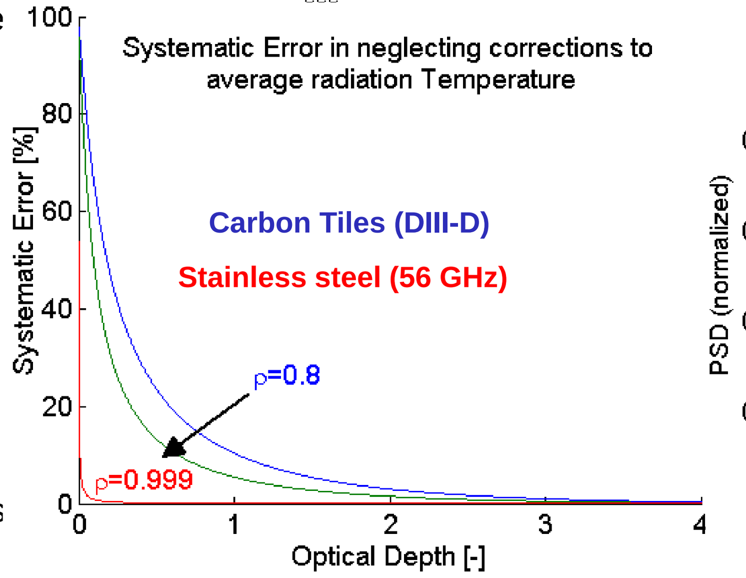
where ρ is the effective reflectivity, τ is the optical depth of radiation at a given frequency.

- The electron temperature from ECE is determined by iterating upon the optical depth for 2nd harmonic X-mode and using the electron density from Thomson Scattering.



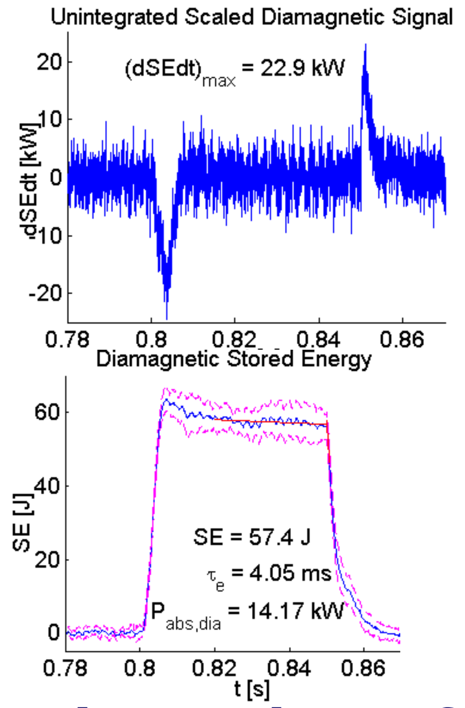


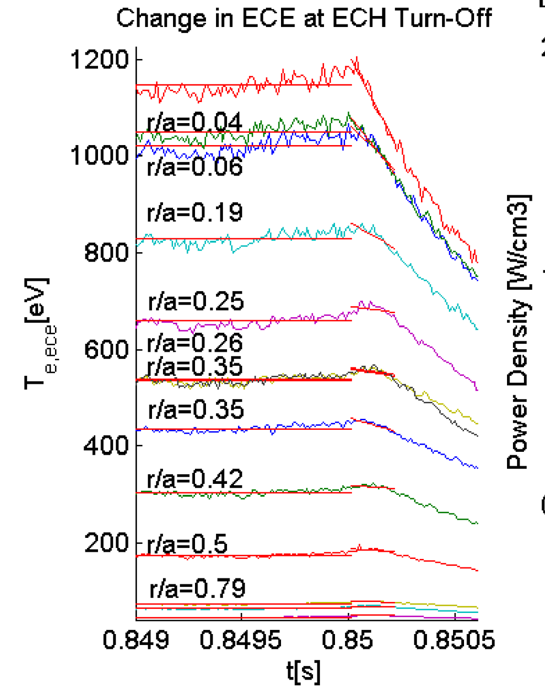
- $T_{r,\omega}$ must be corrected for finite optical depth, τ, to keep the systematic error in T_e below 10% in HSX plasma.
- The effective reflectivity, ρ, is expected to be between 0.8 and 0.99 in HSX and a value of 0.9 is used above.
- The finite solid angle subtended by the ECE antenna is significant near the axis where 1D and 2D analytic calculations overestimate τ (1D>2D>3D).
  - $\tau_{1D} = \int_0^L 2Im k_\omega ds$, along the beam-axis
  - $\tau_{2D} = \frac{1}{\Delta Z}\int_{\Delta Z}\int_{\Delta R} 2Im k_\omega dR dZ$, weighted by the Gaussian power density of the viewing beam
- Refraction is a small effect but noticeable for HFS channels where analytic calculations underestimate τ.

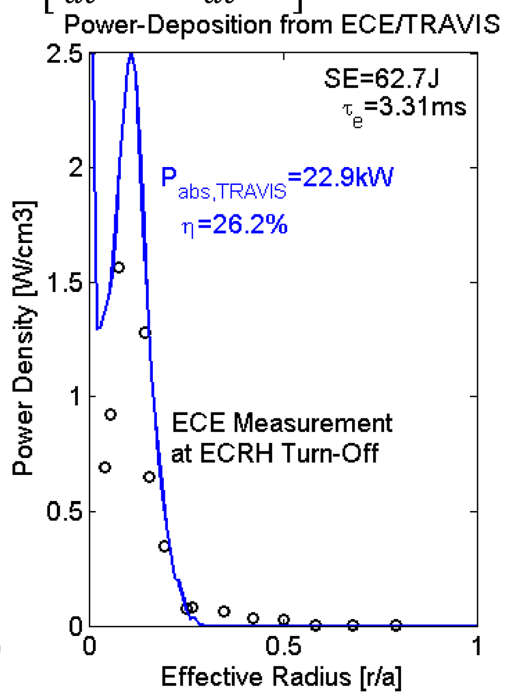


Absorbed Power Measurements and a Comparison to Ray Tracing

$$\frac{d\phi}{dt} \propto \frac{dSE}{dt} \qquad P_{ECRH}\left(\frac{r}{a}\right) = \frac{3}{2}n_e\left[\frac{dT_e}{dt}\Big|_{t^-} - \frac{dT_e}{dt}\Big|_{t^+}\right],$$





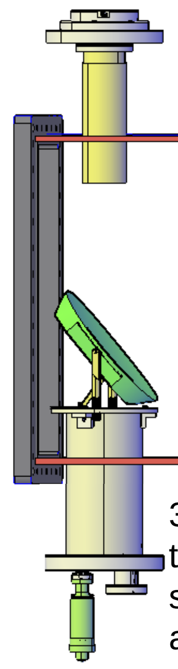


First Results

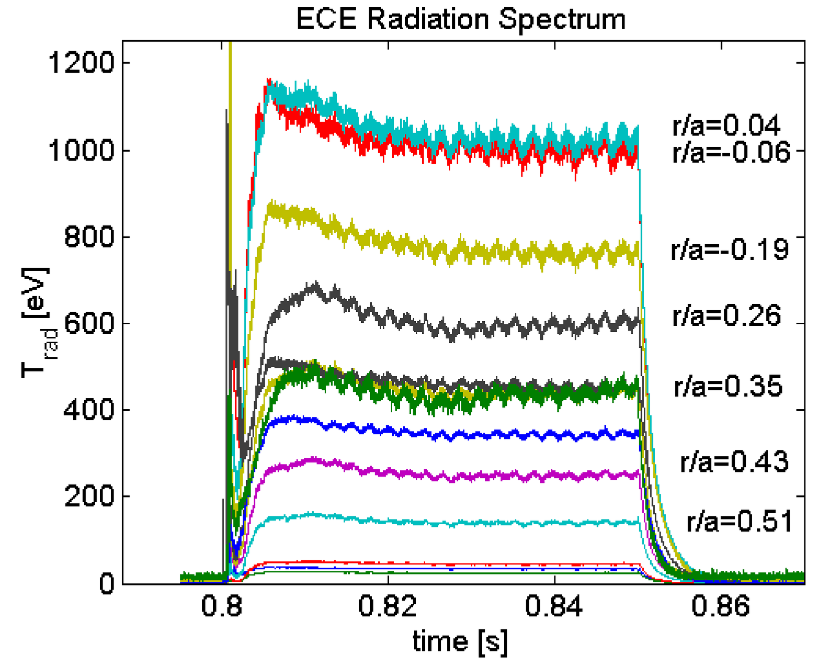
Initial Modulated Heating Experiments

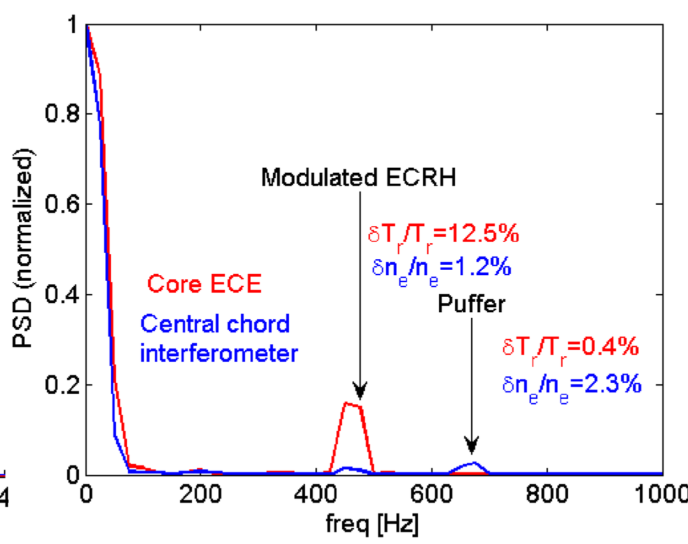
81.5 kW average launched power (28GHz O-mode),

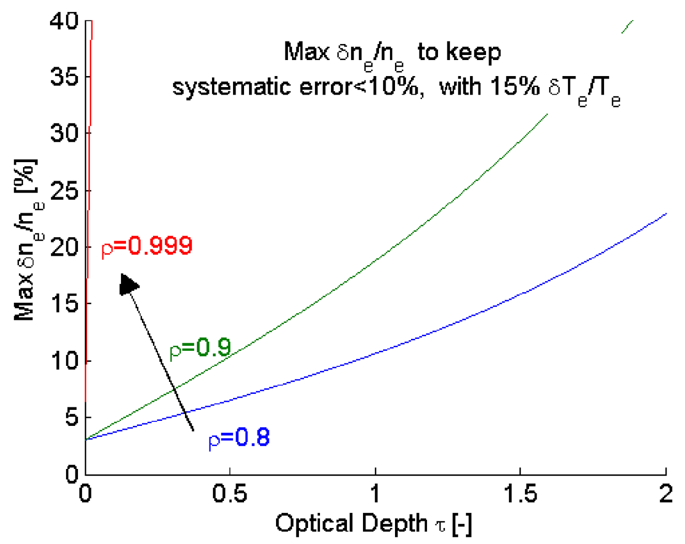
- ECRH1 (44kW) and ECRH2 (40kW) form a target plasma,
- The gun voltage of Gyrotron2 is square-wave modulated from 26 to 25.4 kV at 500 Hz with a 13% modulation depth to produce heat pulses (35-40 kW, 6% total power)
- **The modulation appears on the ECE radiation temperature with a time-delay!**



3D model of the ECRH2 steerable antenna





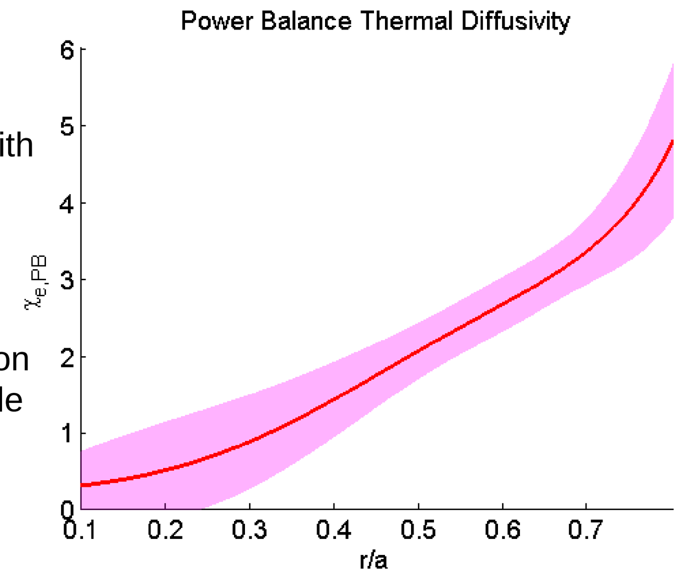


Power Balance Thermal Diffusivity

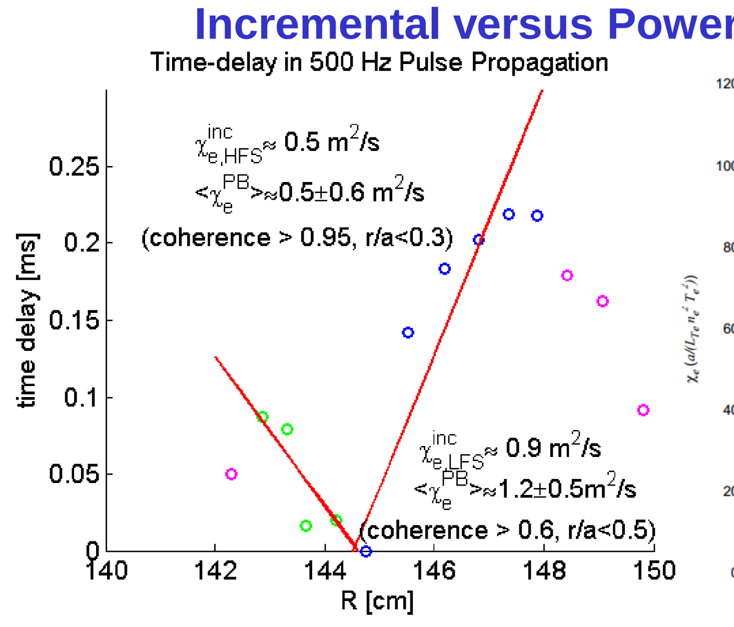
- In steady-state, an effective power-balance thermal diffusivity, χ_{eff}^{PB}, can be defined to characterize the heat transport about an operating point.

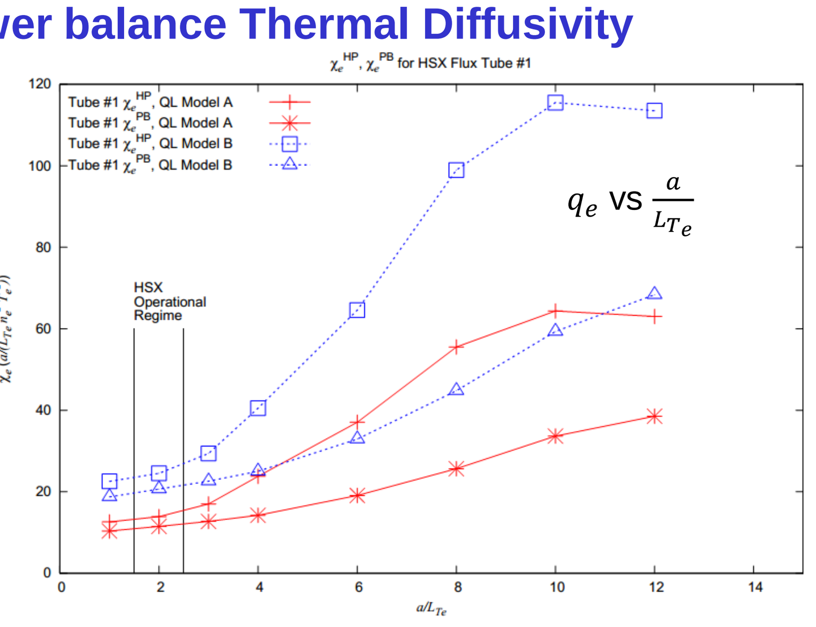
$$\chi_{eff}^{PB} = \frac{\langle\chi_s|\nabla\rho|^2\rangle}{\langle|\nabla\rho|^2\rangle} = -\frac{\frac{d\rho}{dV}\int\langle P_{ECRH}\rangle\frac{dV}{d\rho}d\rho}{n_s\langle|\nabla\rho|^2\rangle\frac{dT_s}{d\rho}},$$

- A least-squares minimization procedure with χ_e^{PB} as the fit parameter for T_e allows rigorous error analysis and yields an effective power-balance diffusivity across the minor-radius of HSX.
- Temperature and density are from Thomson Scattering, and the power deposition profile is from ray tracing (at left) .



Incremental versus Power balance Thermal Diffusivity





- The incremental thermal diffusivity determined from the phase delay yields good agreement between the incremental and volume averaged power balance thermal diffusivity.
  - The phase delay is determined from the cross-power spectral density of a reference ECE channel near the core with each ECE channel that has coherence greater than 0.95 on the HFS and 0.6 on the LFS.
  - The gradient in the phase delay is determined by a linear-fit of time-delay versus squared separation, Δ^2, where Δ is the linear distance between the reference and each ECE channel, and the time delay is $t_d = -\varphi/\omega_{mod}$.
  - The incremental thermal diffusivity is determined from $\chi_e^{inc} = \frac{1}{8}\Delta^2/t_d$ and is a volume average measurement due to the fitting procedure used for the time-delay gradient.
  - The volume average power-balance thermal diffusivity is $\langle\chi_e^{PB}\rangle = \frac{1}{V(\rho_{ece})}\int_0^{\rho_{ece}}\chi_e^{PB}\frac{dV}{d\rho}d\rho$.
  - The power balance thermal diffusivity takes into account the flux-surface geometry term, $\langle|\nabla\rho|^2\rangle$, while the incremental analysis of the phase is in a cylindrical geometry.
- Cold pulses generated by the neutral gas puffer propagate inwards while heat pulses generated from ECRH modulation propagate outward.
- Linear gyrokinetic simulations, performed for this experiment as part of a collaboration with the Princeton Plasma Physics Laboratory, are dominated by TEM turbulence and predict $(a/L_{T_e})_{crit} \lesssim 3$ and $\chi_e^{inc}/\chi_e^{PB} \approx 1 - 2$ at the half-radius using the quasi-linear assumption.

Future Work

- Analysis of the incremental thermal diffusivity resulting from the amplitude decay and including the actual geometry of HSX are left for future work.
- An absolute calibration of the HSX ECE radiometer will be performed, and a new local oscillator will be installed to remove spurious modes of the gyrotron at ECE frequencies.
- A parameter scan in modulated ECRH experiments that will yield the local power deposition and the local thermal diffusivity profiles as a function of density and ECRH power.
- A comparison of the incremental thermal diffusivity measured in the quasi-symmetric magnetic configuration with a magnetic configuration in which the symmetry is broken.

References

[1] Marushchenko, Nikolai B., Volker Erckmann, Hans J. Hartfuss, Mattias Hirsch, Heinrich P. Laqua, Henning Maassberg, and Yuri Turkin. "Ray Tracing Simulations of ECR Heating and ECE Diagnostic at W7-X Stellarator." *Plasma and Fusion Research* 2 (2007): S1129–S1129.

[2] Guttenfelder, W., J. Lore, D. T. Anderson, F. S. B. Anderson, J. M. Canik, W. Dorland, K. M. Likin, and J. N. Talmadge. "Effect of Quasihelical Symmetry on Trapped-Electron Mode Transport in the HSX Stellarator." *Physical Review Letters* 101, no. 21 (November 17, 2008): 215002.

[3] Ryter, F, Y Camenen, J C DeBoo, F Imbeaux, P Mantica, G Regnoli, C Sozzi, et al. "Electron Heat Transport Studies." Plasma Physics and Controlled Fusion 48, no. 12B (December 2006): B453–B463.

54th Annual Meeting of the Division of Plasma Physics, October 29 - November 2, 2012, Providence, RI