Experimental Observation and Integrated Modeling of Electron Heating by Helicon Waves in DIII-D

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General Atomics

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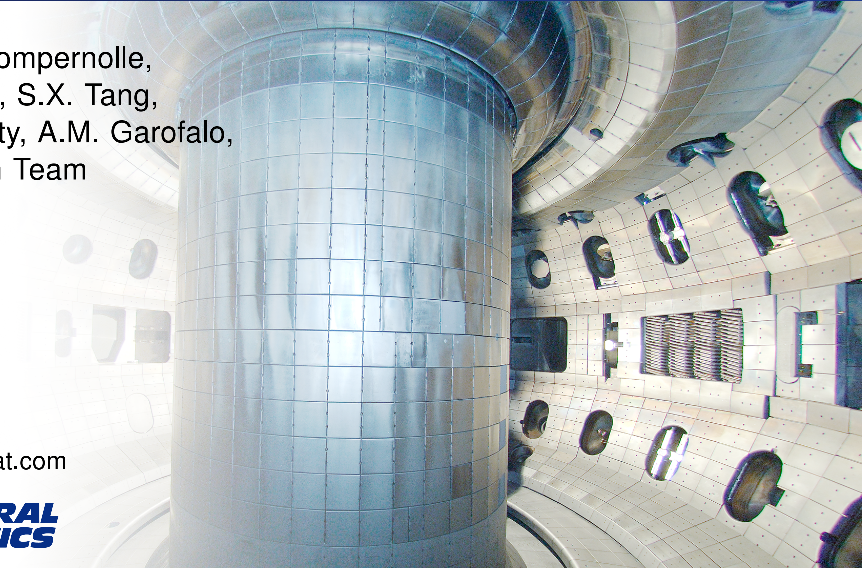

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Motivation and Main Results

- **Motivation**: fast waves in the lower hybrid frequency range (helicon) can provide off-axis current drive needed for non-inductive, steady-state scenarios

- **Goal**: combine δT_e fluctuation measurements with time-dependent integrated modeling in order to assess wave absorption in helicon modulation experiments
  - Necessary to validate models before using to design future scenarios

- **Main results**:
  - Experimental evidence of core electron heating in L mode DIII-D discharges
  - Integrated simulations support interpretation of observed δT_e profiles
  - GENRAY predictions are consistent with initial estimates of helicon absorption

Outline

- Physics Background and Approach
- Experimental Evidence of Core Electron Heating
- Estimated Power Absorption
- Integrated Modeling Approach
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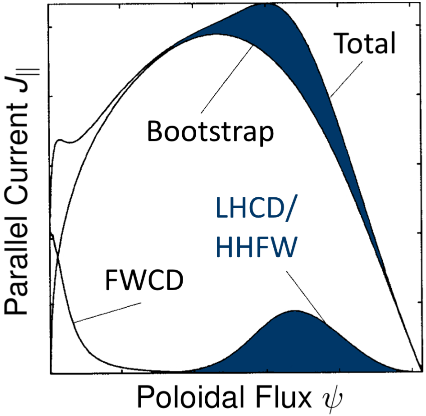
Mid-Radius Current Drive Is Needed for Reactor Scenarios

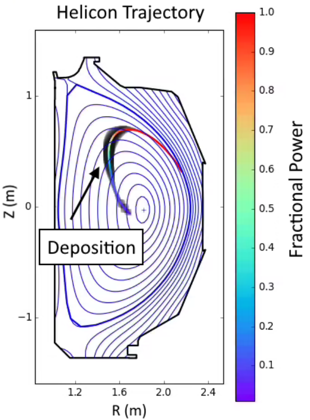
- Steady state scenarios require efficient, non-inductive off-axis current drive[1]
- DIII-D has been studying methods for off-axis radio frequency current drive
  - Top launch ECCD (since 2019)
  - **Helicon current drive** (2021)
  - HFS lower hybrid current drive (2024)
- Whereas ECCD is localized near $\omega \approx n\omega_{ce}$, helicon and lower hybrid current drive occur due to Landau damping, when $\omega/k_{||} \approx v_{||,e}$
  - Off-axis absorption for sufficiently high β_e



[1] S.C. Jardin *et al*. Fusion Eng. Des. **38**, 27 (1997)

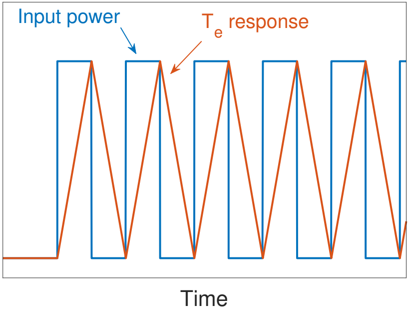
Helicon Wave Can Provide Off-Axis Current Drive

- **Helicon**: fast wave in the lower hybrid range of frequencies ($f_{ci} \ll f \ll f_{ce}$)
  - DIII-D helicon antenna: 476 MHz, $n_{||} = 3$
- Off-axis absorption can drive non-inductive current necessary to help sustain advanced scenarios[2]
- MW-level helicon system has been commissioned on DIII-D with 2 s pulse lengths, robust load resilience
- Initial goal: demonstrate helicon power absorption in L mode and validate against integrated modeling



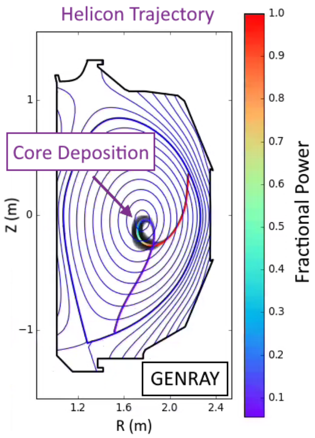
[2]R. Prater *et al.* Nucl. Fusion **54**, 083024 (2014)

Investigating Helicon Absorption With Power Modulation

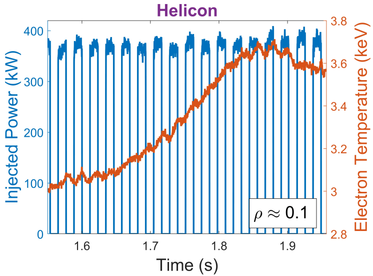


- **Direct heating**: modulated helicon power $\rightarrow$ modulated δT_e response at same frequency, lagging by 90° (ideally)
  - Transport effects distort this picture when modulation is not sufficiently fast
    - However, faster modulation leads to smaller amplitude fluctuations
- Use cross-spectral analysis techniques with Fourier transforms to average over many cycles
- Compare to same analysis with modulated ECH, assumed to be well-understood

Helicon Modulation Is Not Visible in Raw ECE Trace



- GENRAY predicts core deposition with $\approx$ 50% first pass absorption in L mode shot 195182
- Average of 350 kW power injected by helicon antenna
  - Measured by probes, after any transmission losses
- Lack of obvious ECE modulation motivates use of cross spectral analysis to boost signal to noise



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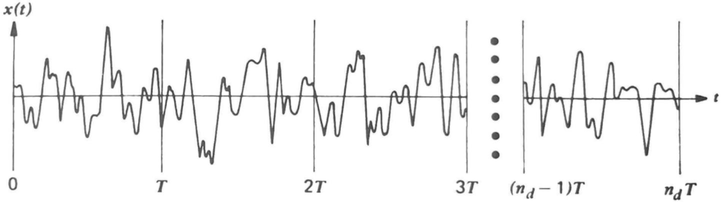
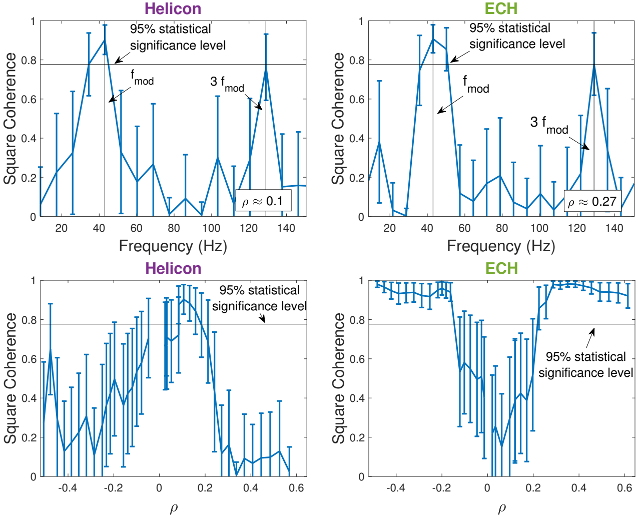
Ensemble Averaging Is Necessary to Quantify Coherence

- Let $P(t)$ be the modulated input power (helicon or ECH) and $T_e(t)$ be the output
  - Then $\hat{P}(f) = F\left[P(t)\right]$ and $\hat{T}_e(f) = F\left[T_e(t)\right]$ are their Fourier images
- **Square coherence**: $\gamma^2 = \frac{|\langle \hat{T}_e^* \hat{P} \rangle|^2}{\langle \hat{P}^* \hat{P} \rangle \langle \hat{T}_e^* \hat{T}_e \rangle} \approx 1$ only when $\phi_P(t) \approx \phi_{T_e}(t)$
  - $\langle \ldots \rangle$ denotes ensemble averaging, by chopping the time series into n_s segments
  - Significance test: $\gamma^2 > 1 - \alpha^{\frac{1}{n_s - 1}}$ rejects the null hypothesis with uncertainty α
- Dividing into more segments improves statistics, but reduces frequency resolution



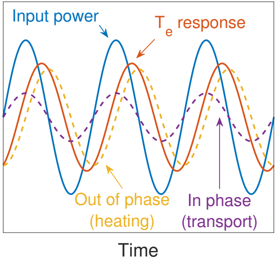
Coherent δT_e Response to Helicon on Core ECE Channels

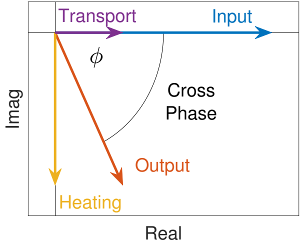
- Both helicon and ECH shots have square coherence peaking at $f_0 = 43$ Hz and $3f_0 = 129$ Hz
  - Square wave modulation has only odd harmonics
  - Coherent peaks exceed 95% significance level
- Helicon coherence at f_0 peaks in the core
  - ECH resonance at $\rho \approx 0.2$
- Statistical error bars result from ensemble average



Cross Phase Characterizes Heating vs Transport Response

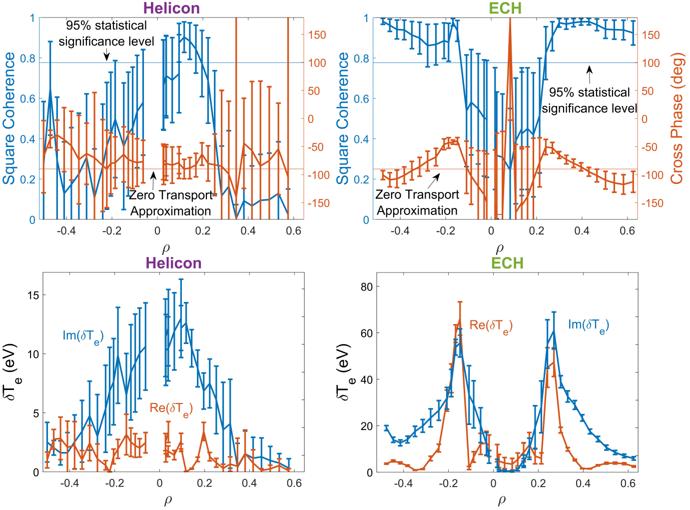
- Measured T_e response includes both heating and transport effects
- Out of phase component results from heating $\text{Im}[\delta T_e(f)] = \frac{\text{Im}[\langle \hat{P}^* \hat{T}_e \rangle]}{\langle \hat{P}^* \hat{P} \rangle} \hat{P}$
- In phase component $\text{Re}[\delta T_e(f)]$ occurs due to transport or direct diagnostic pickup
- **Cross phase** $\tan \phi(f) = \frac{\text{Im}[\delta T_e]}{\text{Re}[\delta T_e]}$ quantifies this relationship ($\phi \to -90^\circ$ for zero transport)





Measured δT_e Profiles Show Core Heating

- Cross phase is near ideal -90° for nearly all channels
  - ECH is more coherent, but also has more transport
    - Cross phase deviates from $-90°$ near peak deposition
- Out of phase δT_e peaks in core, agreeing with ray tracing predictions



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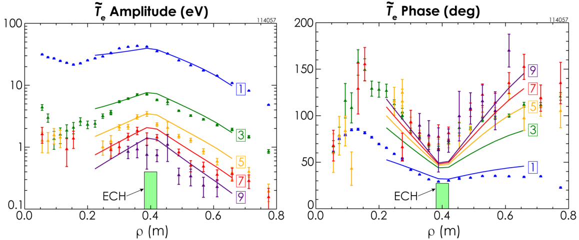
Electron Transport Effects Complicate Extracting Absorbed Power From δT_e Measurements

- Electron energy conservation relates source profile $\hat{S}(f,\rho)$ to $\hat{T}_e(f,\rho)$ via transport

$$-D\nabla^2 \hat{T}_e(f,\rho) + V\nabla \hat{T}_e(f,\rho) + \left(\frac{1}{\tau} + i\frac{3}{2}\omega\right)\hat{T}_e(f,\rho) = \frac{\hat{S}(f,\rho)}{n_e}$$

- Diffusion and convection can smear out the fluctuations and alter the cross phase

- Rigorous approach: fit multiple harmonics of $\hat{T}_e$ data to determine values of transport coefficients[3]
  - Present helicon data does not have high enough signal to noise to fit multiple harmonics



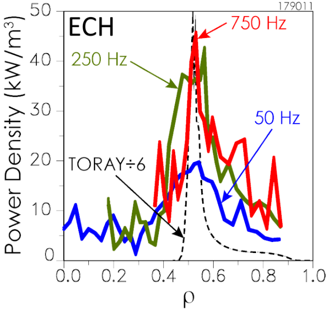
[3] C.C. Petty *et al.* 23rd RFPPC, Hefei, China (2019)

Zero Transport Approximation Yields an Oversimplified Estimation of Power Deposition

- If modulation is much faster than transport, can assume direct heating response
- Then summing over all frequencies in a square wave of height S_{max} gives the total absorption as a function of δT_e measured only at the modulation frequency f_0

$$P_{abs} = \int S_{max}(\rho)dV \approx \frac{3\pi}{4}\omega_0 \int n_e(\rho)\text{Im}[\hat{T}_e(f_0,\rho)]dV$$

- ECH modulation experiments indicate $f_0 = 43$ Hz is not within this zero transport regime[4]
- **Compromise**: adjust this approximation via calibrated ECH measurements and modeling

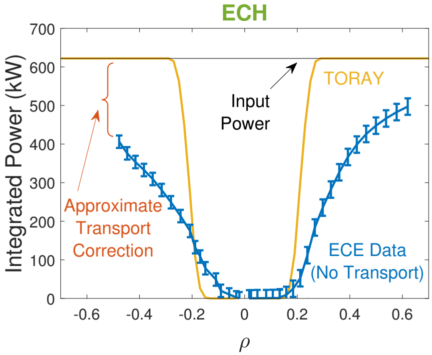


[4]C.C. Petty *et al.* 61[st] APS DPP, Fort Lauderdale, FL (2019)

ECH Experiments Used to Adjust for Transport in Helicon Experiments

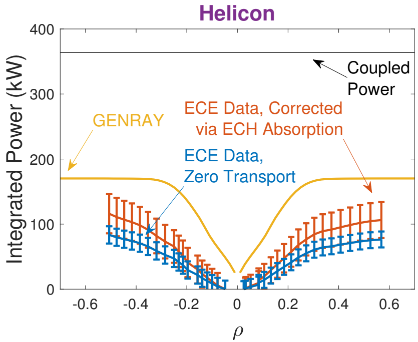
- Significant shortfall exists when calculating P_{abs} from δT_e data without transport for ECH modulation shot
- **Leap of faith**: assume the ECH transport correction is the same for helicon
  - Note: ECH deposition is much more narrow than helicon, localized at $\rho \approx 0.2$
  - Crude approximation, not a precise accounting of transport effects

$$P_{abs}^{HK} \approx P_{meas}^{HK}(ECE)\frac{P_{abs}^{ECH}(TORAY)}{P_{meas}^{ECH}(ECE)}$$



Preliminary Estimate of Transport Adjusted Helicon Absorption Consistent With GENRAY Prediction

- Transport correction factor calculated from ECH modulation
- GENRAY predicts 30 - 50 kW of power near the axis, where ECE does not cover



	ECH	Helicon
Power Coupled to Plasma	622 kW	354 kW
TORAY/GENRAY Predicted Absorption	622 kW	**166 kW**
ECE Data (Zero Transport)	452 ± 43 kW	80 ± 9 kW
Absorbed Power Transport Adjustment	Ratio of 1.4 ± 0.1	**111 ± 24 kW**

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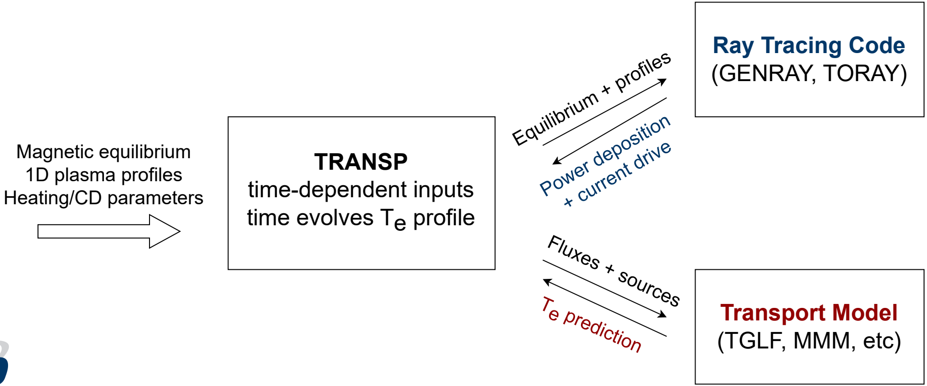
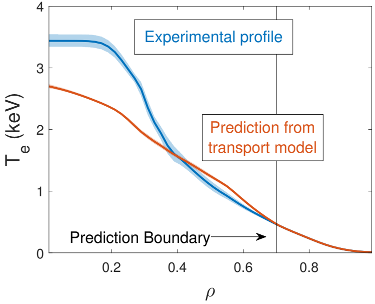
Time-Dependent Integrated Modeling With TRANSP

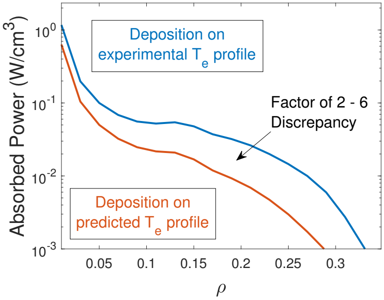
- TRANSP loops over a ray tracing code and transport model at each time step in order to predict the helicon deposition and δT_e response over time
- Comparing predicted δT_e to ECE measurements aids experimental interpretation



Helicon Absorption is Sensitive to Errors in T_e Profile Evolution

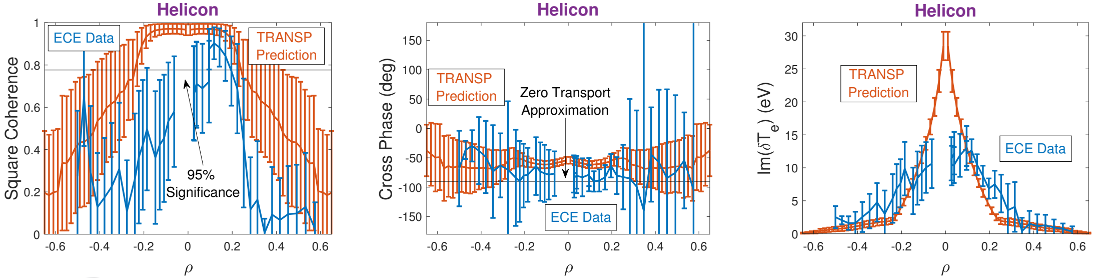
- Anomalous transport model evolves T_e in time, not just δT_e
- Due to sensitivity of helicon absorption in weak damping regime (L mode), reasonable uncertainty in T_e profile prediction strongly modifies deposition
  - This is also true for uncertainties in experimental profile reconstructions
  - Hotter target plasmas with stronger absorption may ameliorate this issue





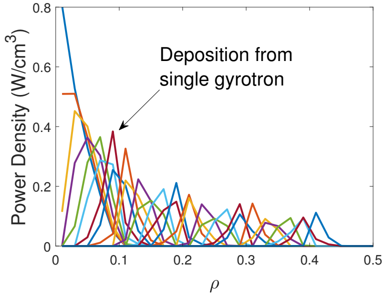
Helicon ECE Measurements Agree With Core Deposition Predicted by Simulations

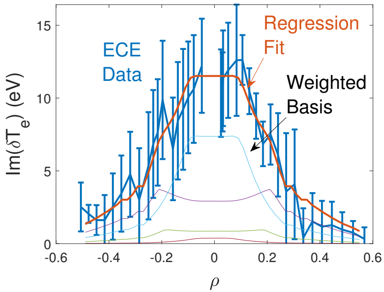
- Simulations have more peaked deposition than ECE measurements
  - Predicted δT_e magnitude is less reliable due to sensitivity to predicted T_e profile
- Coherence is much higher in TRANSP, but has similar peaked profile
- Good agreement between flat cross phase profile in simulations and experiment



Alternative Approach to Inferring Power Absorption: Use TRANSP to Solve the Inverse Problem

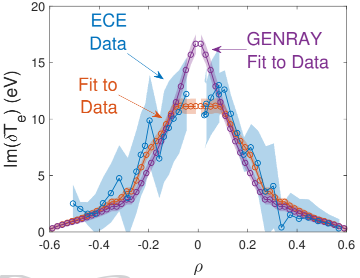
- **Question**: what power deposition profile would correspond to the measured $\delta \hat{T}_e$?
- Use an artificial array of ECH gyrotrons to create basis functions
  - Avoids sensitivity of helicon deposition on T_e profile predicted by TRANSP
- Linear regression to find weights of each gyrotron to reproduce observed $\delta \hat{T}_e$

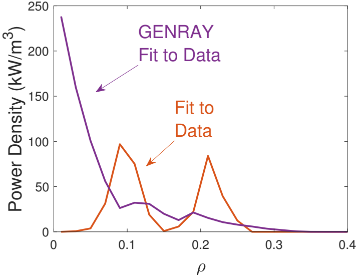


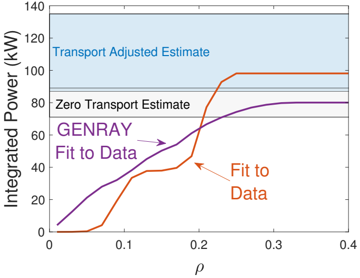


Regression Fit to Data Significantly Less Peaked Than GENRAY Prediction

- Fit to data is the direct fit to the ECE data
  - 100 kW of total heating is consistent with purely empirical estimate of 111 $\pm$ 24 kW
- GENRAY fit to data uses the predicted power deposition, scaled to fit $\delta\hat{T}_e$
  - More strongly peaked $\delta\hat{T}_e$ near the axis, very similar to the best fit elsewhere







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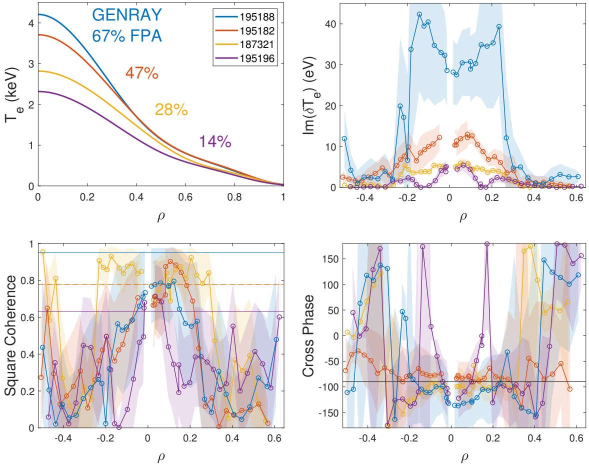
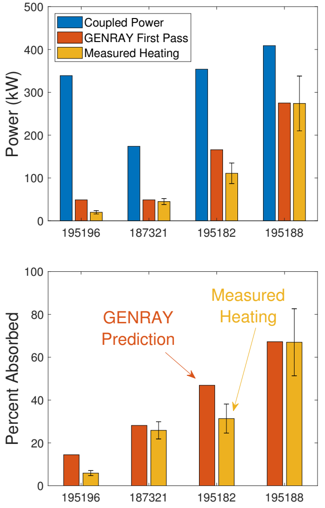
Consistent Core Deposition When Scanning Equilibrium T_e

- Equilibrium T_e scanned by varying ECH power
- GENRAY predicts core absorption in each case
- Coherence is near or above 95% significance level, cross phase near $-90°$, and $\delta\hat{T}_e$ is core-localized
  - Note: different coupled helicon power in each shot



Inferred Power Absorption Scales With Predicted First Pass Absorption

- Surprisingly good agreement in some cases between GENRAY first pass absorption and observed heating
  - More reliable: trend in absorption across shots
- Error bars are likely understated
  - Only partially quantified substantial uncertainty in transport adjustment
- Future experiments with full first pass absorption will distinguish between prompt vs multi-pass losses



Summary and Future Work

- Helicon modulation experiments in L mode DIII-D plasmas were investigated with cross spectral analysis and time-dependent integrated simulations

Summary

- Core electron heating observed in DIII-D L mode experiments
- Time-dependent integrated modeling in qualitative agreement with measurements
- Preliminary estimate of helicon absorption is consistent with GENRAY prediction

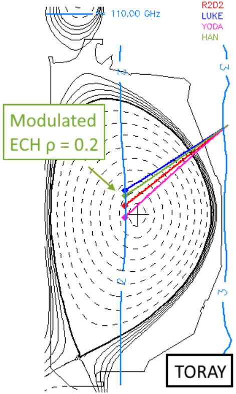
Future Work

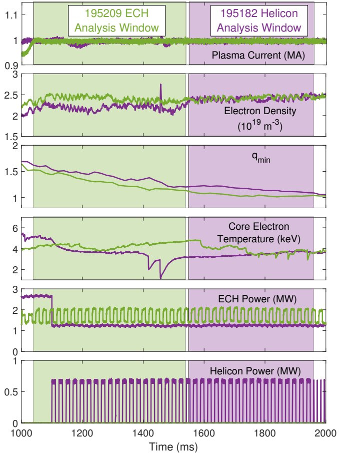
- Reduce modeling error in T_e profile evolution to improve δT_e reliability for helicon
- Upcoming experiments will more precisely quantify absorption and current drive
- Once validated, use time-dependent integrated modeling to explore the role of helicon current drive in advanced scenarios

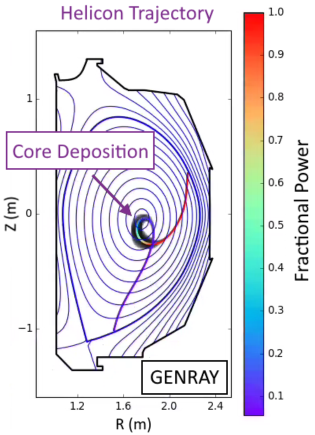
Work supported by US DOE under DE-FC02-04ER54698

Backup Slides

Helicon and ECH Modulation Experiments







Two Quantities for Estimating δT_e Response

- Defining the transfer function $\hat{H}$ via $\hat{T}_e(f) = \hat{H}(f)\hat{P}(f) \Rightarrow \hat{H} = \langle \hat{P}^* \hat{T}_e \rangle / \langle \hat{P}^* \hat{P} \rangle$,

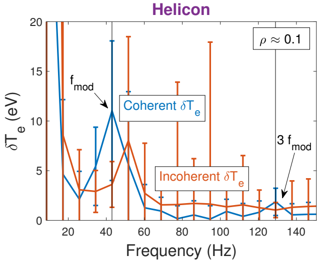
1. **Coherent output spectrum**: $\delta T_e^2(f) = |\hat{H}|^2 \langle \hat{P}^* \hat{P} \rangle = \frac{|\langle \hat{P}^* \hat{T}_e \rangle|^2}{\langle \hat{P}^* \hat{P} \rangle}$
   - Weighting by coherence is built in (equivalently, $|\hat{H}|^2 \langle \hat{P}^* \hat{P} \rangle = \gamma^2 \langle \hat{T}_e^* \hat{T}_e \rangle$)
   - Complementary quantity: incoherent spectrum: $(1 - \gamma^2) \langle \hat{T}_e^* \hat{T}_e \rangle$
   - Drawback: no information on phase between $\hat{P}$ and $\hat{T}_e$
2. **Out of phase response**: $\delta T_e(f) = \mathrm{Im}[\hat{H}] |\hat{P}| = \frac{\mathrm{Im}[\langle \hat{P}^* \hat{T}_e \rangle]}{\langle \hat{P}^* \hat{P} \rangle} \hat{P}$
   - Cross phase: $\tan \phi(f) = \frac{\mathrm{Im}[\delta T_e]}{\mathrm{Re}[\delta T_e]}$ characterizes heating vs transport response
   - Does not include coherence directly, very noisy away from modulation frequency
   - Drawback: overstates Δf resolution due to interpolating $\hat{H}(f)$ onto grid of $\hat{P}(f)$

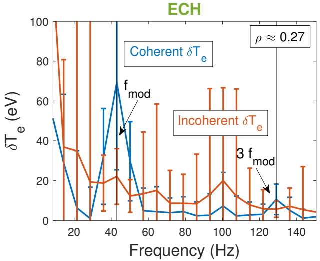
- Relative error formulas exist for both quantities[5] (errorbars in plots)

[5] J.S. Bendat *et al*. Journal of Sound and Vibration **59**, 405 (1978)

Coherent Output Spectrum Distinguishes Coherent vs Incoherent Fluctuations

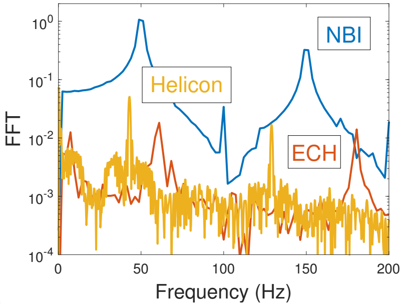
- **Coherent spectrum**: $\delta T_e^2(f) = \frac{|\langle \hat{P}^* \hat{T}_e \rangle|^2}{\langle \hat{P}^* \hat{P} \rangle} = \gamma^2 \langle \hat{T}_e^* \hat{T}_e \rangle$
  - Weighting by coherence is naturally built-in
  - Incoherent spectrum: $(1-\gamma^2)\langle \hat{T}_e^* \hat{T}_e \rangle$
  - No information on phase between $\hat{P}$ and $\hat{T}_e$
- Both ECH and helicon shots show clear peaks in coherent spectrum at f_0 and $3f_0$
- 50 Hz peak in helicon data is due to NBI modulation
  - Differentiated from the response to the helicon modulation via this decomposition

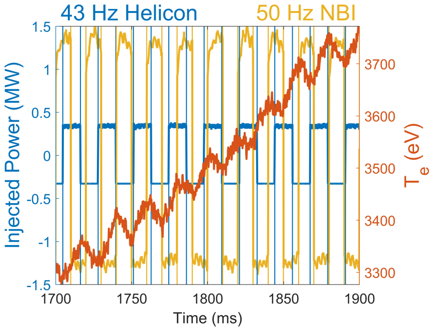




Visible T_e Modulation Influenced by NBI

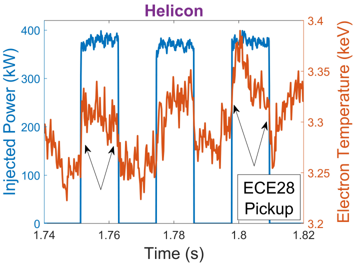
- Beam modulation used to reduce NBI power, avoid transition into H mode
- Unfortunately, 50 Hz NBI modulation quite close to 43 Hz helicon modulation

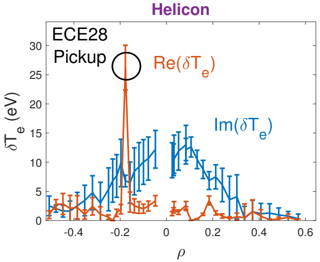


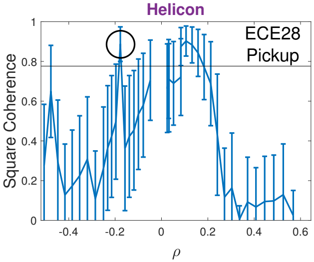


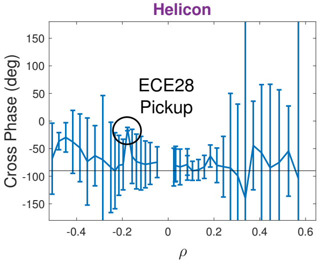
Direct Pickup Has Different Signature From Heating

- ECE channel 28 is polluted when helicon operates
- Signatures of direct pickup:
  - Rapid rise of T_e response
  - Very high coherence
  - Wrong cross phase
    - Signal is in phase
- Other ECE channels do not have these dramatic features
  - Helps to rule out pickup









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Zero Transport Limit May Provide Lower Bound on Absorption

- Electron energy conservation equation in most basic form may be written

$$\underbrace{\int \frac{\partial}{\partial t}\left(\frac{3}{2} n_e T_e\right) d^3x}_{\text{direct heating}} + \underbrace{\int \nabla \cdot Q \, d^3x}_{\text{transport}} = \underbrace{\int S \, d^3x}_{\text{source}} = P_{\text{abs}}$$

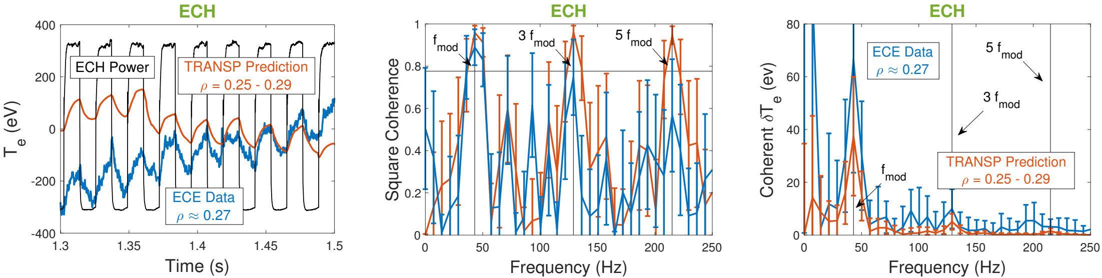
- Here, $Q = -n_e D \nabla T_e + n_e V T_e$ is the heat flux. Rewriting the transport term yields

$$\int \frac{\partial}{\partial t}\left(\frac{3}{2} n_e T_e\right) d^3x + \oint Q \cdot dA = \int S \, d^3x = P_{\text{abs}}$$

- So long as heat is not flowing in from the boundary, neglecting transport necessarily represents a lower bound on the true absorption

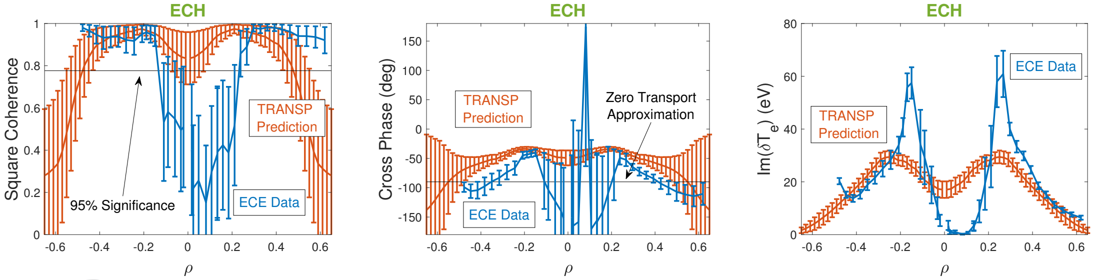
Consistent Response to Modulated ECH in ECE Data and TRANSP Predictions

- Coherent δT_e response visible in time trace in ECE data and TRANSP simulations
- Experimental coherence falls into noise at higher frequency harmonics
- Calculated δT_e is within statistical errorbars for measurements and simulations



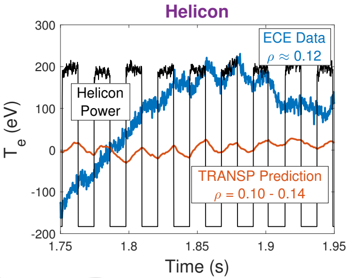
Spatial Fluctuation Profiles in Reasonable Agreement With Simulations for Modulated ECH

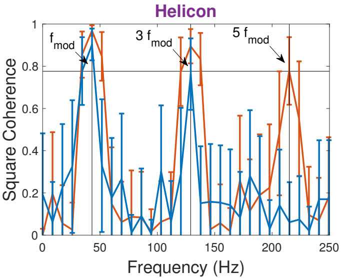
- 1D TRANSP simulations are mirrored to compare to measurements
  - Radial ECE array spans HFS ($\rho < 0$) and LFS ($\rho > 0$)
- TRANSP + TORAY/MMM predict similar δT_e width, though less prominent peaks
- Measured fluctuations are much more hollow near the axis than in TRANSP

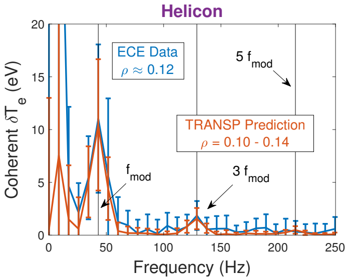


Modulated Helicon Response Buried in ECE Trace, Has Coherent Features Consistent With TRANSP Predictions

- $\approx$ 10 eV δT_e response not clear in ECE time series
  - Visible modulation is actually at 50 Hz, due to NBI blips (rigorously distinguished)
- Even in TRANSP, helicon coherence is weaker than for ECH modulation
- Coherent δT_e has similar frequency dependence at a given location







Averaging Coherence Across Many ECE Channels Improves Statistical Power

- Single ECE channel often only shows clear peaks in coherence at f_0 and $3f_0$
- Combining multiple channels averages out noise
  - Average over $|\rho| < 0.25$
- 95% significance level shown for a single channel
  - Work in progress: rigorously calculating this for combining channels