Experimental Evidence of Helicon Wave Heating and Current Drive in DIII-D

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General Atomics

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GENERAL ATOMICS

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**: experimentally measure the electron temperature and current profile response to helicon injection in order to assess absorption and current drive
  - Necessary to validate models before using to design future scenarios
- **Main results**:
  - Core electron heating directly observed in both L and H mode plasmas
  - Strong and reproducible experimental evidence of helicon current drive in DIII-D
  - Experimental estimates of absorption and current drive are consistent with GENRAY

Outline

- Introduction
- Evidence of Electron Heating
- Evidence of Current Drive

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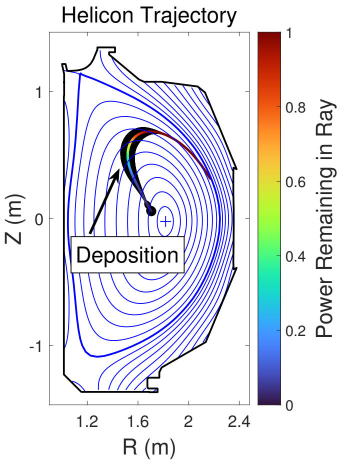
Helicon Wave Can Provide Off-Axis Current Drive

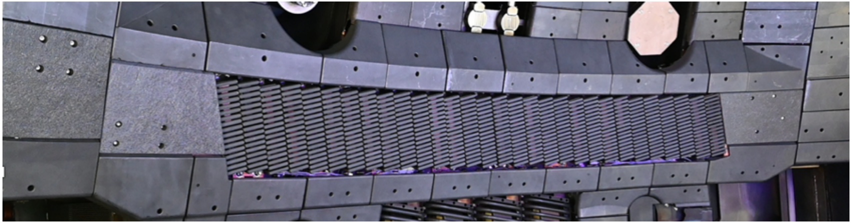
- **Helicon**: fast wave in the lower hybrid range of frequencies ($f_{ci} \ll f \ll f_{ce}$)
  - DIII-D traveling wave antenna: 476 MHz, $n_{||} = 3$
- Absorption via Landau damping, scales with β_e
  - Current drive efficiency scales with T_e/n_e and $\omega/k_{||}v_{th,e}$
- Off-axis absorption can drive non-inductive current necessary to help sustain advanced scenarios[1]
- Physics goal: demonstrate helicon heating and current drive in DIII-D plasmas and validate against modeling



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

MW-level DIII-D Helicon System Has Been Used for Physics Experiments

- 30 module comb-line traveling wave antenna, 1.5 m in total length
  - Robust load resilience to ELMs consistently observed
- Designed to inject power from either end to drive current in either toroidal direction
- 1.2 MW maximum klystron power, reliably operated around 700 – 800 kW
  - Routinely coupled 300 – 400 kW to plasma for up to 2 s
- No influx of impurities was measured during helicon injection



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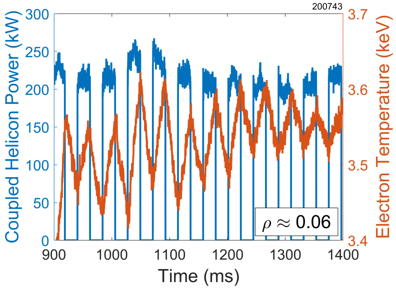
Definitive Observation of Electron Heating Due to Helicon

- Helicon power modulated at fixed frequency to isolate coherent electron heating
- **Square coherence** measures synchronization of T_e with helicon power over time
  - Clear peaks at $f_{mod} = 23$ Hz, $3f_{mod} = 69$ Hz, and $5f_{mod} = 115$ Hz on core ECE
    - Square coherence far exceeds 95% statistical significance level



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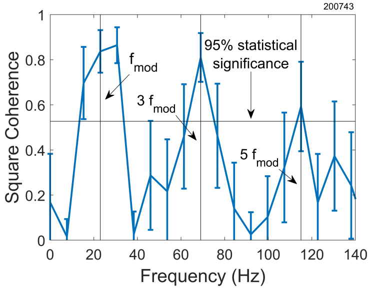

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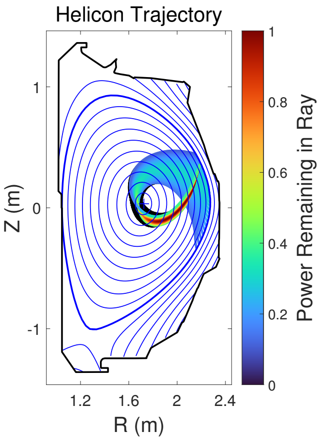
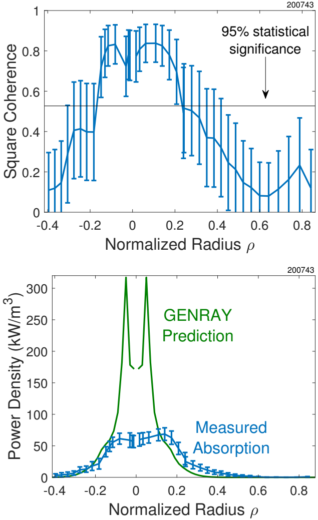
Measured δT_e Profiles Show Core Heating

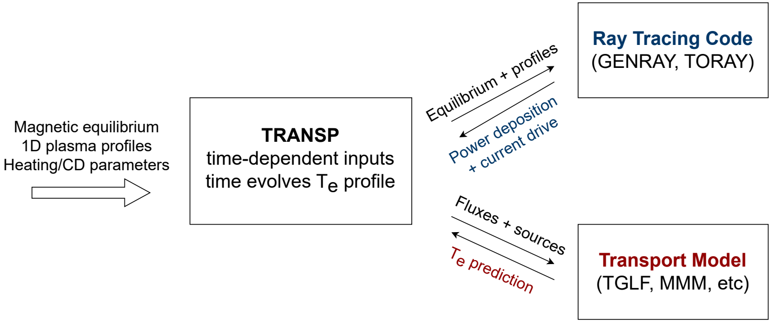
- GENRAY predicts core deposition with $\approx$ 40% first pass absorption in L mode
  - 210 kW power measured leaving the antenna
- Square coherence and δT_e peak in core, agreeing with ray tracing predictions
- Preliminary estimate of 90 ± 20 kW of heating
  - Need transport modeling to improve accuracy





Time-Dependent Integrated Modeling With TRANSP

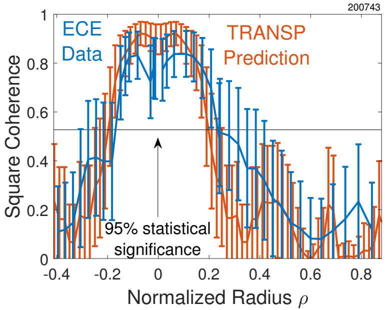
- TRANSP loops over the GENRAY ray tracing code and MMM[2] turbulent transport model in order to predict the helicon deposition and δT_e response over time
- Comparing predicted δT_e to ECE measurements aids experimental interpretation

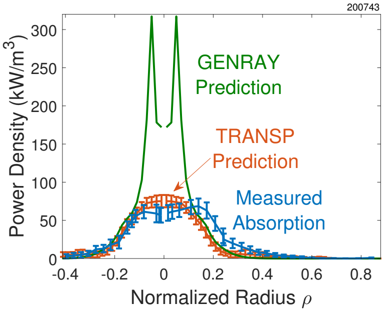


[2] T. Rafiq *et al.* Plasma **6**, 435 (2023)

δT_e Measurements Consistent With Time-Dependent TRANSP Simulations

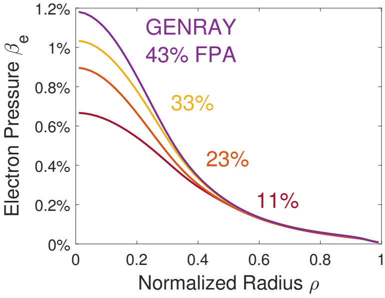
- Coherence is slightly higher in TRANSP, with very similar peaked profile
- δT_e response predicted by TRANSP reproduces broad measured deposition
  - Explains difference between GENRAY vs ECE measurements via transport effects

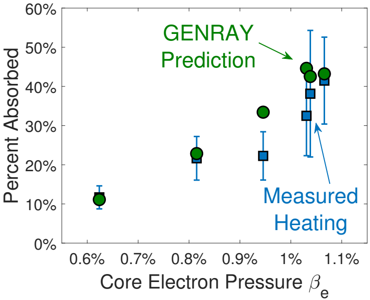




Observed Power Absorption Scales With Predicted First Pass Absorption

- Core β_e scanned across shots with varying ECH to scan predicted absorption
- Observed electron heating tracks first pass absorption predicted by GENRAY
  - Measurements shown without transport corrections
- Clear heating also observed in H mode, absorption more difficult to quantify





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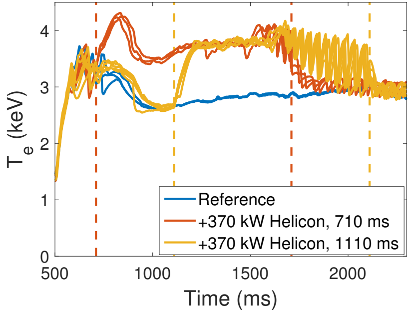
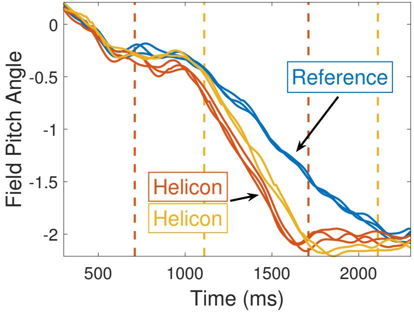
Helicon Injection Changes MSE Evolution

- Only one side of antenna available, unable to compare co- vs cntr-current drive
  - Use ECH comparison shots to separate heating vs current drive effects instead
    - Inject helicon power continuously to drive co-I_p current, without any modulation
- MSE drops faster in shots with helicon than with comparable EC heating

ECE Data ($\rho \approx$ 0.02)



MSE Data ($\rho \approx$ 0.1)



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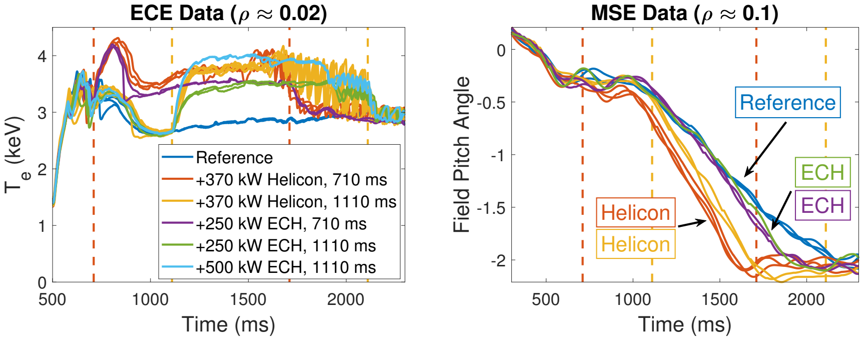
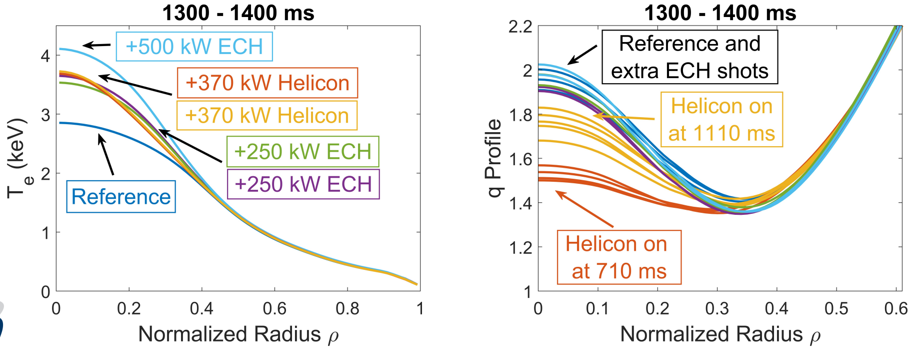


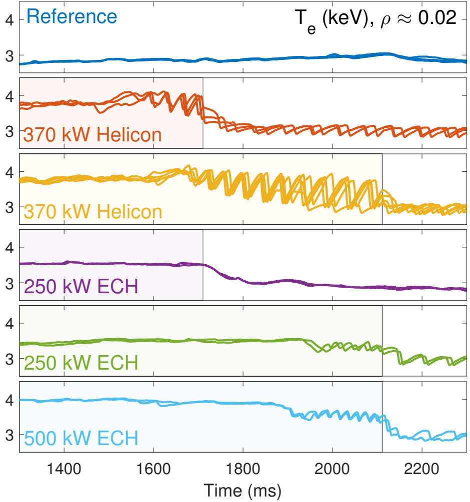
T_e and q Profiles Indicate Helicon Heating and Current Drive

- 370 kW coupled helicon power increases T_e by $\sim$ 1 keV relative to the reference
  - Similar T_e profile to 250 kW of ECH deposited at $\rho = 0.1$
    - Somewhat larger than the $\approx$ 47% FPA predicted by GENRAY (175 kW)
- MSE-constrained reconstruction shows q profile flattening due to helicon current



Sawteeth Start Earlier in Helicon Shots

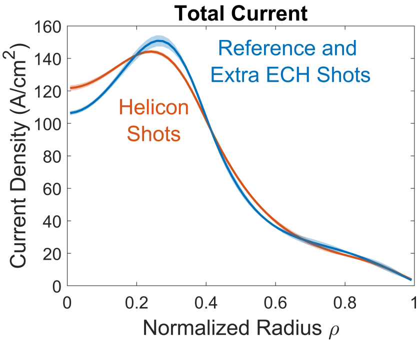
- Sawteeth onset when $q = 1$, providing independent measure of current evolution
- Helicon shots begin sawtoothing long before shots with comparable amount of ECH
- Interpretation: co-I_p helicon current drives q down faster, triggering sawteeth earlier
  - Consistent with MSE and EFIT reconstruction



Helicon Current Determined by Comparing Non-Inductive Current With Reference Shots

- Changes in $J_{||}$ profiles are insufficient to quantify helicon current drive
  - $\int \Delta J_{||}\, dA = 0$ since I_p is unchanged
- Determine change in non-inductive current by subtracting off Ohmic current and “known” non-inductive current sources[3]
- Calculate ΔJ_{NI} between shots with and without helicon to mitigate systematic uncertainties

$$J_H = \Delta J_{||} - \Delta J_{Ohm} - \Delta\left(J_{BS} + J_{NB} + J_{EC}\right)$$

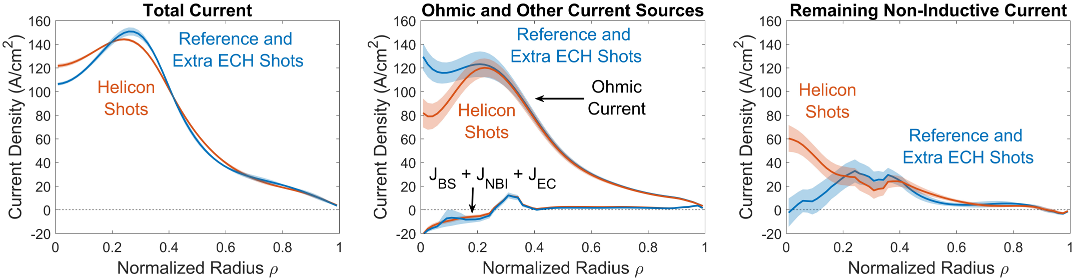


- Average over repeat shots with helicon vs no helicon to reduce uncertainty

[3]C.B. Forest *et al.* Phys. Rev. Lett. **73**, 2444 (1994)

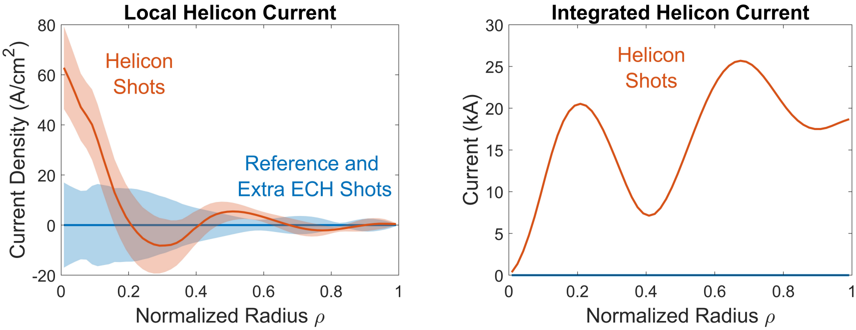
Subtract Ohmic and Other Current Sources To Get Remaining Non-Inductive Current

- $E_{||}$ calculated from MSE-constrained equilibrium reconstruction, neoclassical conductivity from kinetic profile data: $J_{Ohm} = \sigma E_{||} \propto \frac{T_e^{3/2}}{Z_{\text{eff}}} \frac{\partial \psi}{\partial t}$
- Other non-inductive current sources calculated by standard models in TRANSP
- Systematic errors lead to unexplained current near $\rho \approx 0.3$ in reference shots



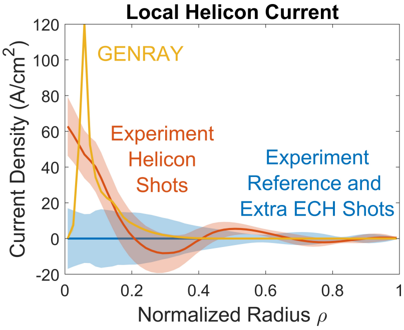
Peaked Helicon Current Profile Within $\rho < 0.2$

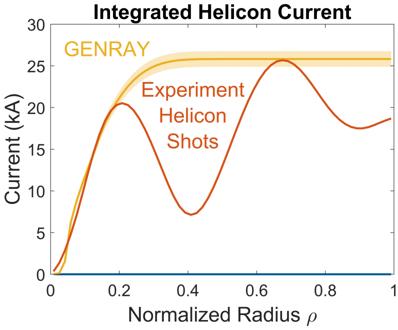
- Helicon current profile consistent with measured heating profile in similar L modes
  - Helicon current density far exceeds the spread among reference and ECH shots
- Preliminary estimate of $\approx$ 20 kA integrated current, at least 10 kA uncertainty
  - Note: shaded regions show average across shots – uncertainties not yet propagated



Measured Helicon Current Drive in Reasonable Agreement With Modeling

- GENRAY predicted current density profile is more peaked than experiment
  - Sensitive to details of ray trajectory due to rapidly decreasing volume near axis
- Integrated current profile in fair agreement, finding similar amount of current enclosed in $\rho < 0.2$ – oscillations likely an artifact of analysis
  - GENRAY prediction for first pass absorption: 150 kA/MW of absorbed power





Main Results and Ongoing Analysis

Main Results

- Core electron heating observed in both L and H mode DIII-D plasmas
  - Time-dependent integrated modeling in qualitative agreement with measurements
- Strong evidence for first observation of helicon current drive on any device
  - Observed changes in L mode current profile can not be explained by heating alone

Ongoing Analysis

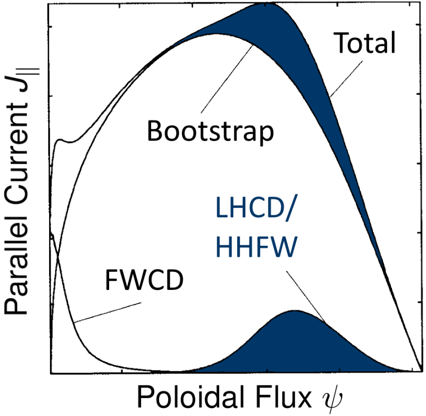
- Calculate H mode power absorption from modulated T_e response
- Refine L mode current drive analysis and quantify experimental efficiency

Work supported by US DOE under DE-FC02-04ER54698. ASIPP and KFE contributed to the manufacturing and procurement of the helicon hardware.

Backup Slides

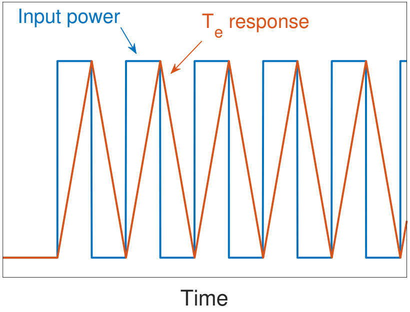
Mid-Radius Current Drive Is Needed for Reactor Scenarios

- Steady state scenarios require efficient, non-inductive off-axis current drive[4]
- 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



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

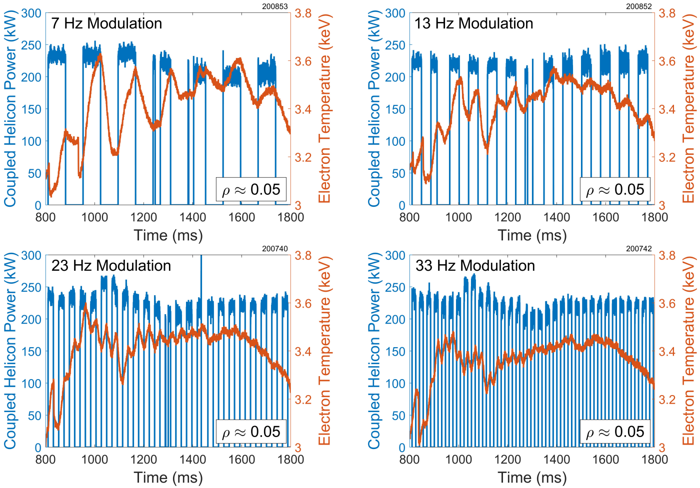
Investigating Helicon Absorption With Power Modulation



- **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

Electron Temperature Responds to Modulation Frequency

- δT_e amplitude increases with longer helicon pulse time
- Frequency scan rules out coincidental δT_e oscillations



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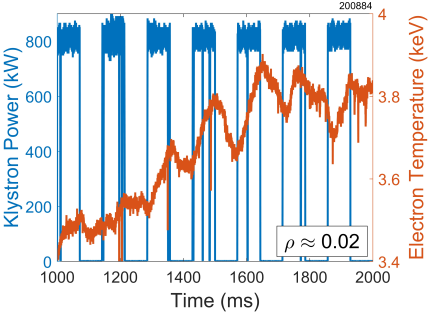
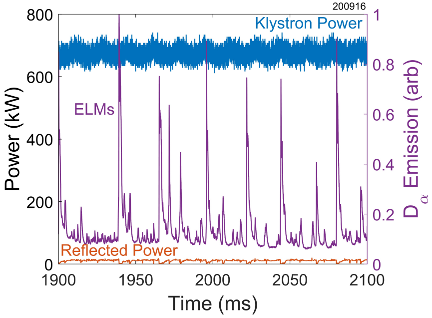
Clear Electron Heating Also Observed in ELMy H mode

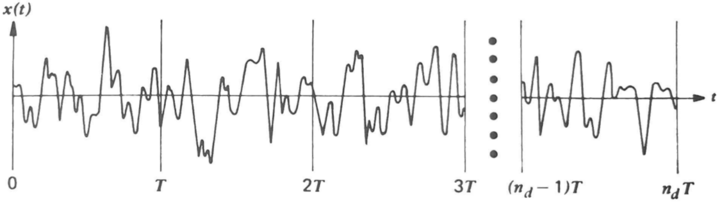
- GENRAY predicts over 90% first pass absorption in these H mode plasmas
  - Absorption still predicted near axis – higher density plasmas push absorption off axis
- Robust load resilience – no substantial rise in reflected power during ELMs





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 $\hat{P}(f) = F[P(t)]$ and $\hat{T}_e(f) = F[T_e(t)]$ 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



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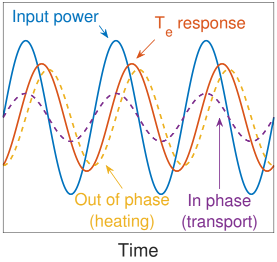
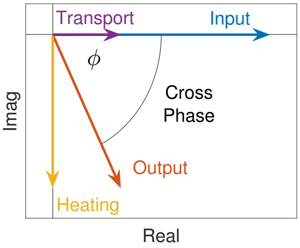
Cross Phase Characterizes Heating vs Transport Response

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





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)

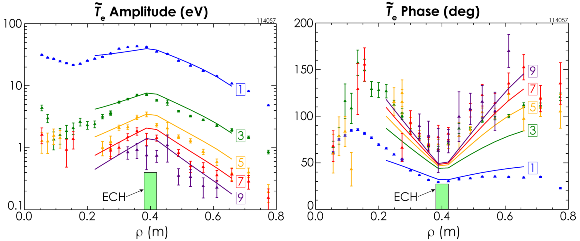
Electron Transport Effects Complicate Extracting Absorbed Power From δT_e Measurements

- 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[6]
  - Present helicon data does not have high enough signal to noise to fit multiple harmonics

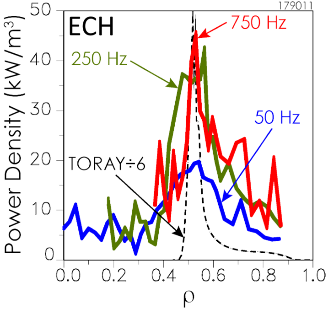


[6] C.C. Petty *et al.* 23rd RFPPC, Hefei, China (2019)

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

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

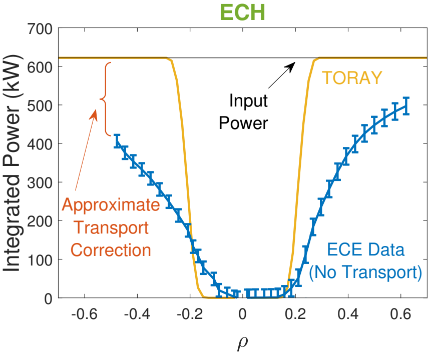


- ECH modulation experiments indicate $f_0 = 23$ Hz is not within this zero transport regime[7]
- **Compromise**: adjust this approximation via calibrated ECH measurements and modeling

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

ECH Experiments Used to Adjust for Transport in Helicon Experiments

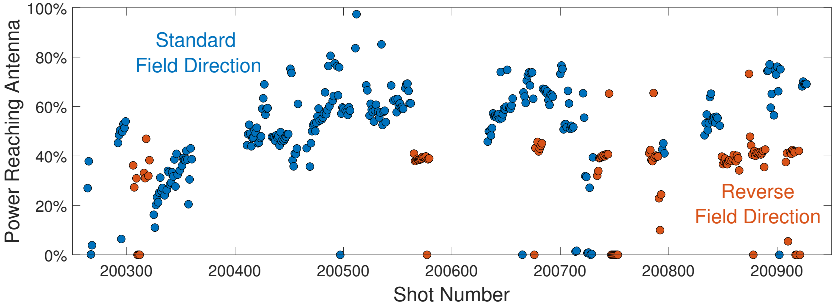
- Significant shortfall exists when calculating P_{abs} from δT_e data without transport for ECH modulation shot
- **Leap of faith**: assume the ECH transport correction is the same for helicon
  - Note: ECH deposition is much more narrow than helicon, localized at $\rho \approx 0.2$
  - Crude approximation,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



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

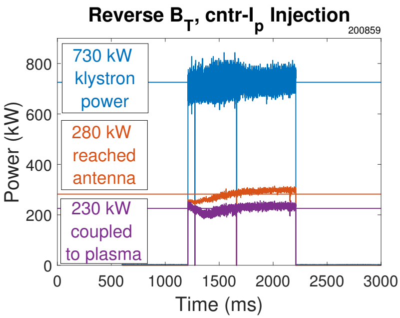
Vacuum Transmission Losses Improve With Conditioning

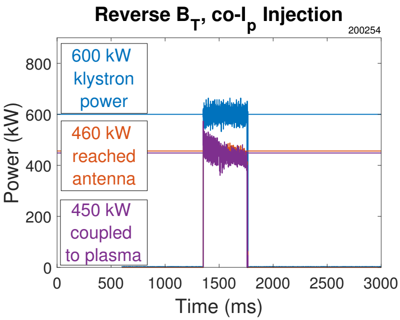
- Antenna designed for “reverse” B_T direction for advanced scenario experiments
  - Antenna conditioning is sensitive to direction of magnetic field
    - Majority of time available for conditioning was in “standard” B_T direction



Vacuum Transmission Losses Depend on Which Side of Antenna is Fed Power

- Magnetic field and plasma current directions unchanged in two shots below
- Vacuum transmission losses were much higher when injecting in cntr-I_p direction





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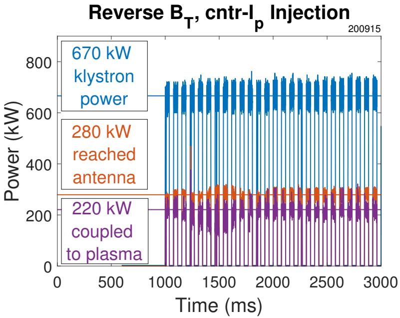
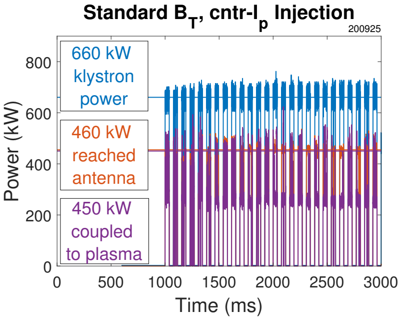
Vacuum Transmission Losses Depend on Field Direction

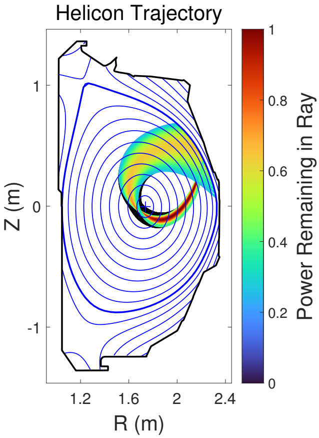
- Magnetic field direction flipped between two shots below
- Vacuum transmission losses were much higher in the reverse B_T direction

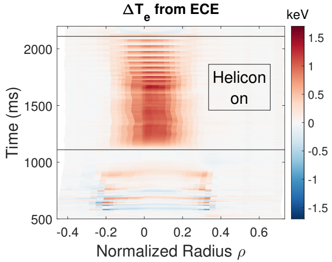




GENRAY Predicts Core Absorption in L Mode Plasma

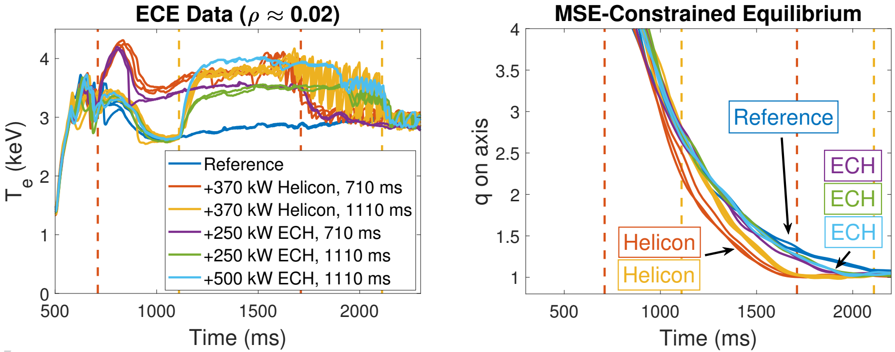
- GENRAY predicts core deposition with ≈ 47% first pass absorption in L mode
  - 370 kW power measured leaving the antenna
- GENRAY predicts ≈ 26 kA helicon current drive
- Unambiguous core heating measured by comparing T_e in shots with and without helicon



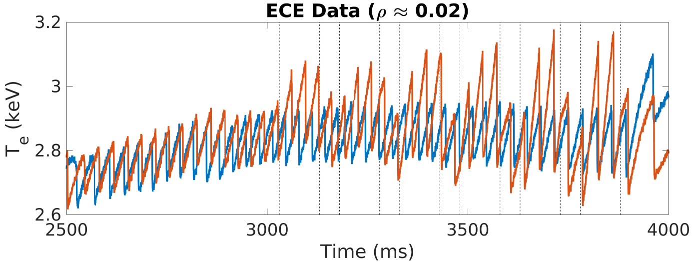


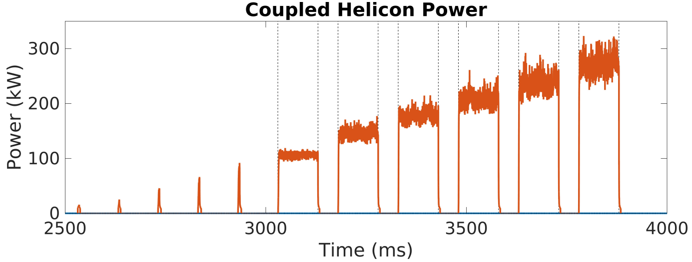
MSE-Constrained EFITs Show Drop in *q* On-Axis

- *q* drops faster on-axis in helicon shots than ECH references that had higher T_e
  - Changes in *q* can not be fully explained by heating – likely helicon current drive



Helicon Power Increases Sawtooth Amplitude





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