Investigation of Core Impurity Transport in Alcator C-Mod EDA H-Mode Plasmas

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Alcator C-Mod

Multi-pulse laser blow-off impurity injector: controlled introduction of impurities

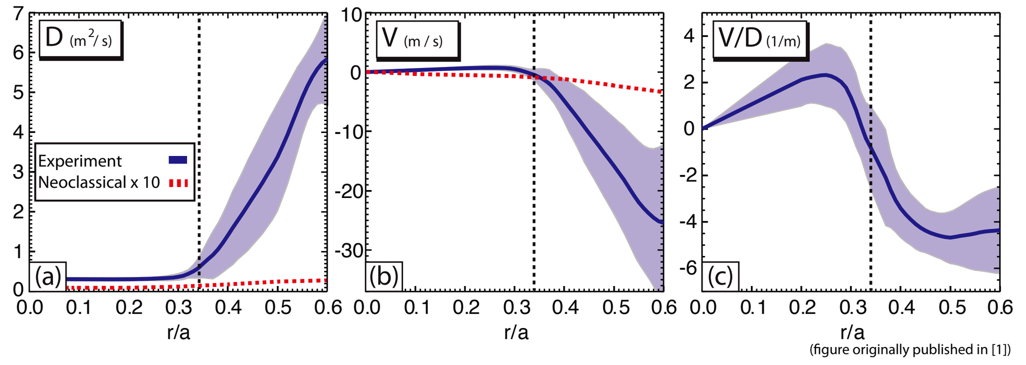
Controlled impurity injections are a very powerful tool to probe transport

- Small (nonperturbative) injection of a non-intrinsic, non-recycling impurity (such as calcium) enables systematic study of impurity transport [1, 2].
- Larger injections are used to induce cold pulses to investigate non-local thermal transport [3].

Hardware overview

- Motorized steering for between-shot positioning.
- Piezoelectric steering for in-shot movement of beam.
- Fast steering and 10 Hz laser repetition rate enables multiple injections into a shot.
- Have utilized up to nine injections in a single discharge.
- Iris diaphragm and linear translation stage enables control over the spot size and power density at slide.

Impurity transport coefficient profiles have been successfully measured for L-mode plasmas



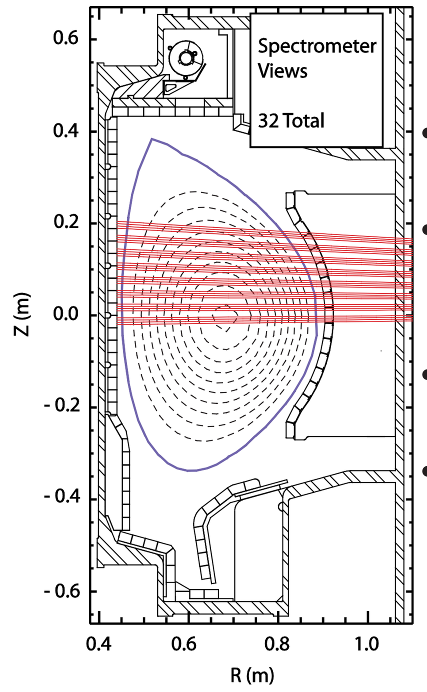
- Iterated with the STRAHL code [4] to find the profiles of the diffusivity D and convective pinch velocity V that match the observed evolution of the Ca XIX emission profile.
- Comparisons to GYRO have been performed, and have found that the GYRO predictions are within the domain of plausibility defined by the experimental uncertainties [1].

Present work seeks to extend, enhance previous techniques

- Extend to EDA H-mode regime.
- Improve quantification of uncertainties.
- Uncertainty quantification (UQ) requires repeated runs of various codes throughout the simulation validation pipeline:
  - Requires automated tools for input preparation and code execution.
  - Requires intelligent UQ methodology to minimize number of computationally-expensive runs needed to adequately sample uncertain parameter space.
- UQ methodology has been applied to preliminary automated profile fitting tool. There are still some issues that must be resolved.

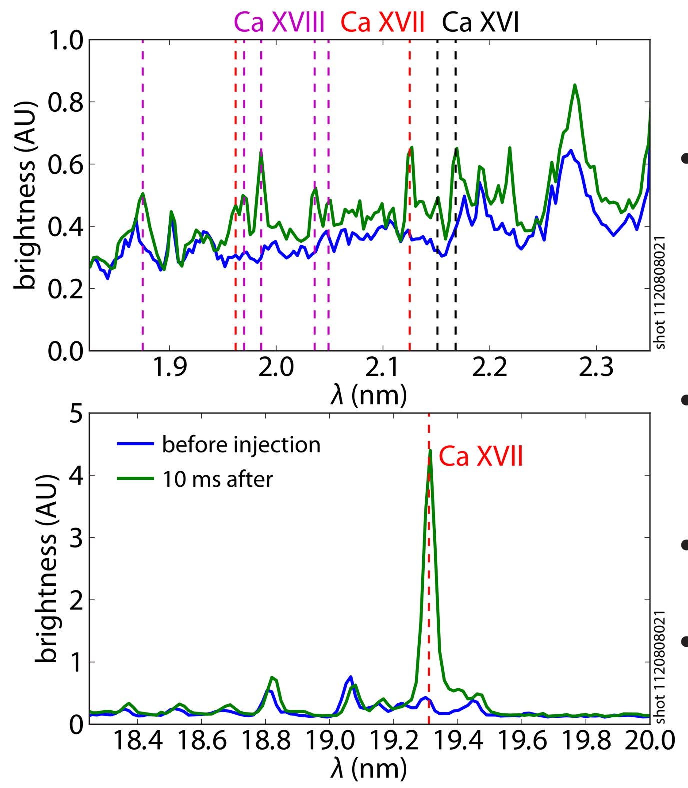
A variety of diagnostics tracks the injection

An x-ray imaging crystal spectrometer observes emission profiles from high charge states



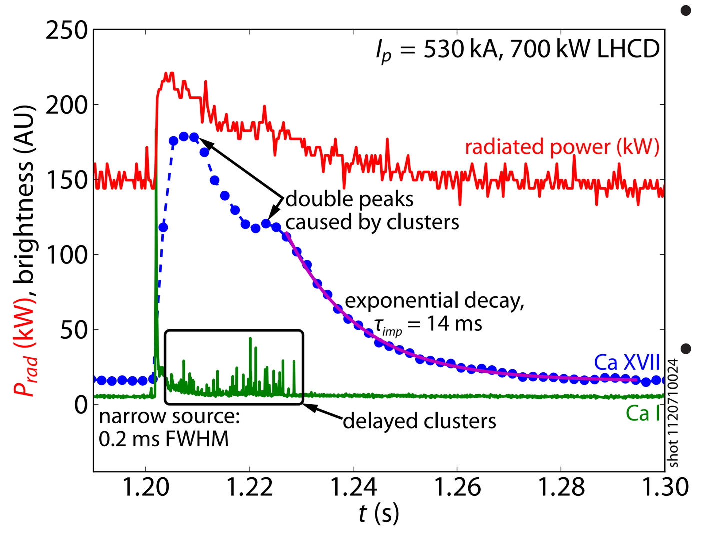
- Calcium is typically injected: non-intrinsic and non-recycling.
- The spectrometer can be configured to view emission from either Ca XIX or Ca XX.
- 32 spatial channels, up to 6 ms time resolution.
- Combining the data from multiple injections at 10 Hz enables an effective time resolution of 2 ms.

Two VUV grating spectrometers observe line-integrated emission from lower charge states



- Two compact, VLS grating, flat-field spectrometers from LLNL EBIT lab [5, 6].
- 1–6.5 nm and 10–29 nm spectral ranges.
- Line-integrated core view.
- 2 ms frame rate.

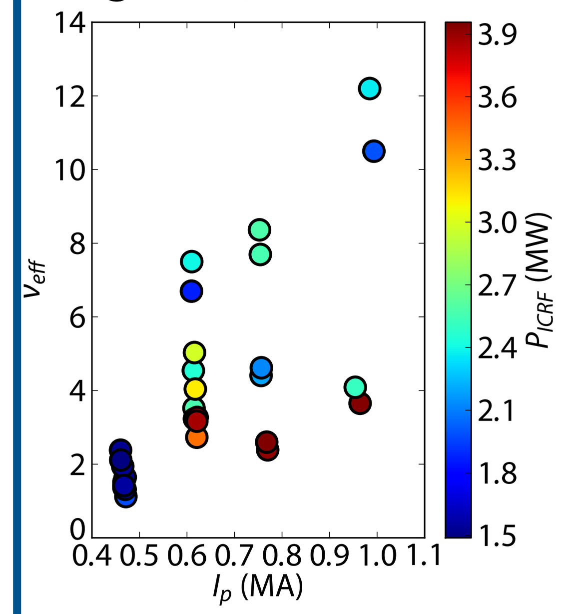
Additional diagnostics provide further information on the injection



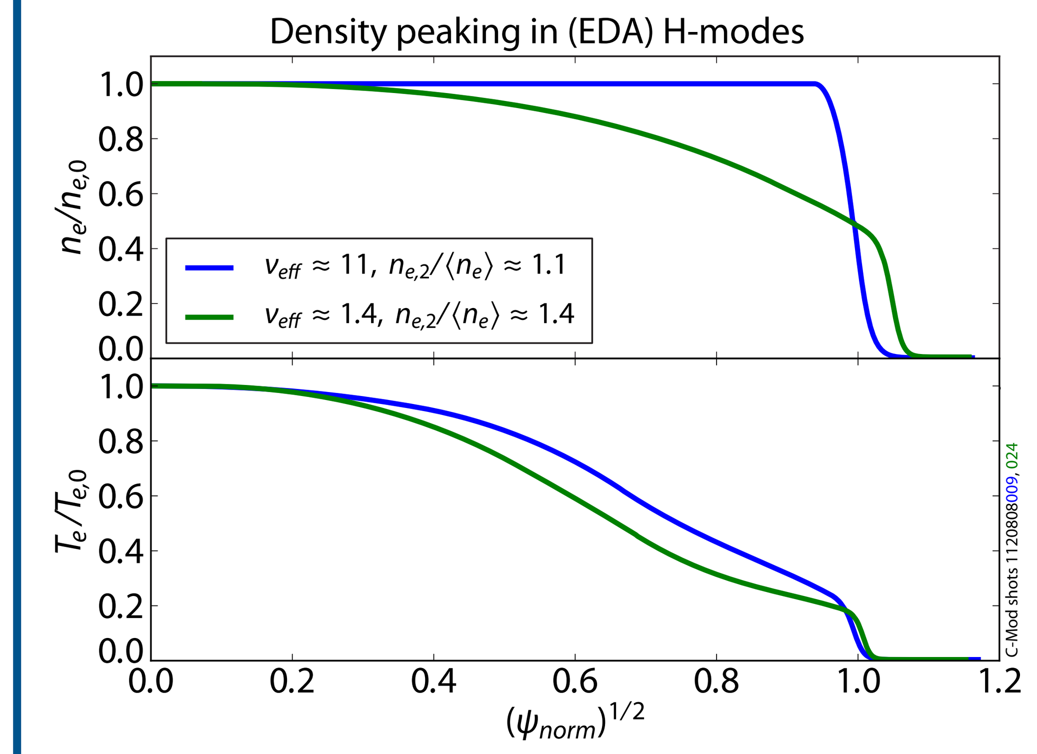
- A variety of soft x-ray diagnostics and bolometers provides information on radiation from all charge states.
- A filtered PMT coaxial with the injector measures the Ca I impurity source.

A broad range of EDA H-mode conditions has been explored

A current/power scan was used to access a wide range of ν_{eff}

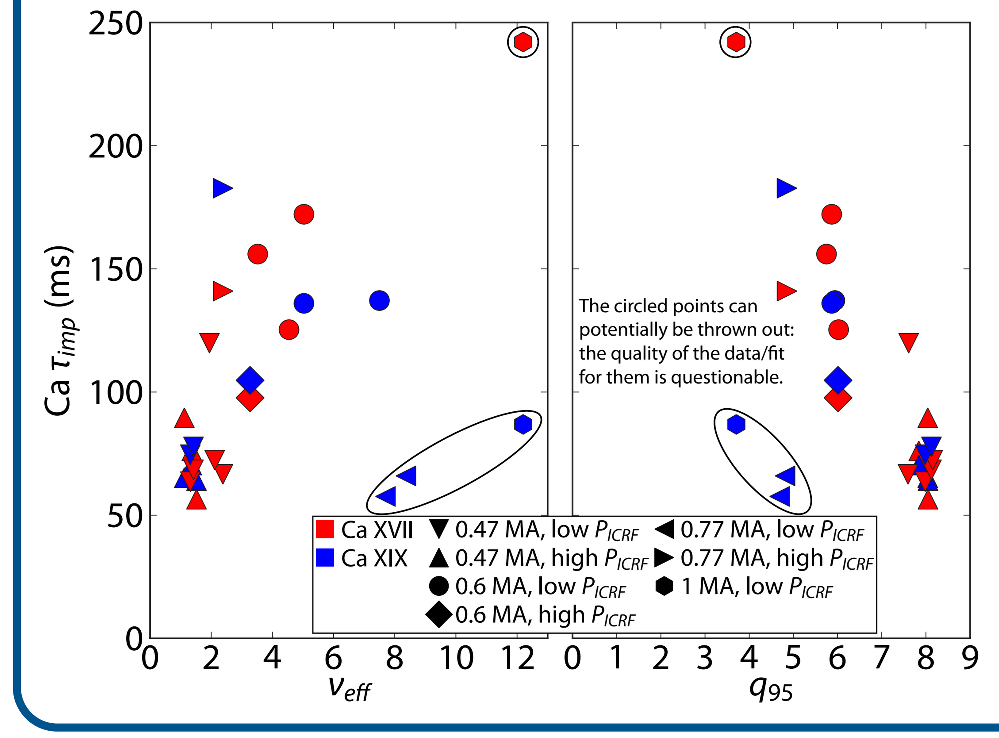


- Density peaking in H-modes has been observed [7] to scale with $\nu_{\text{eff}} = 0.1 Z_{\text{eff}} \langle n_e \rangle R / \langle T_e \rangle^2$.
- A scan of I_p and P_{ICRF} was used to modulate ν_{eff}.
- Ca was injected into the plasmas in order to look for a connection to the main ion particle transport.



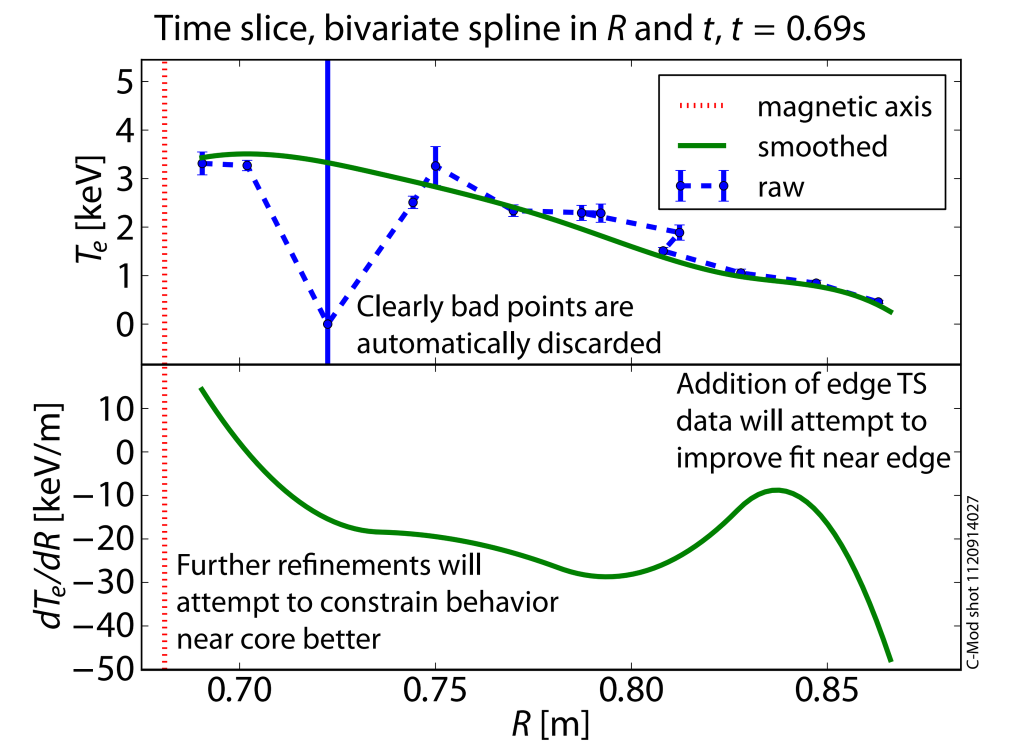
Initial analysis of global confinement results shows dependencies on ν_{eff} and q_{95}

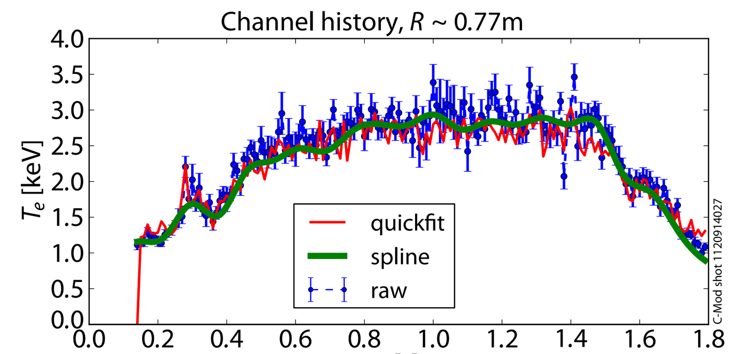
More work is needed to explain the outliers and look at the behavior of the impurity density and transport coefficient profiles.



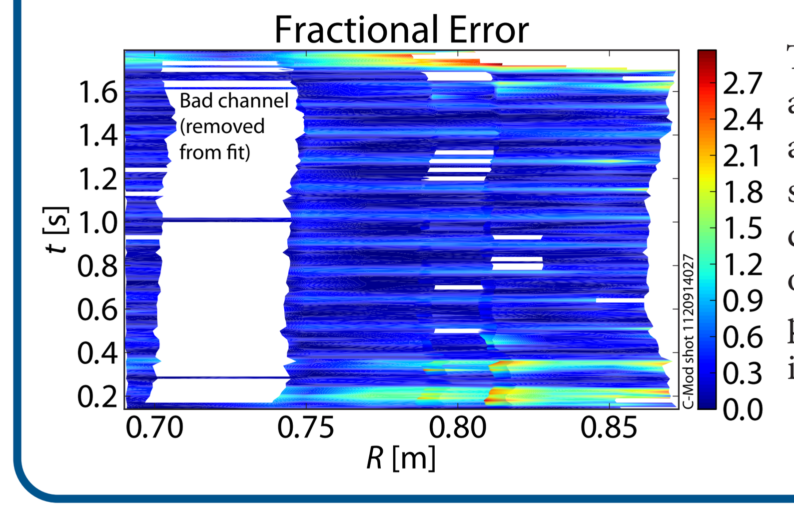
Automated profile smoothing tools are under development to enable better quantification of uncertainty in the analysis

- A key improvement under development for application to these data is a more rigorous approach to uncertainty quantification (UQ).
- Zero-interaction tools for profile smoothing and other input preparation tasks are needed to enable UQ studies.
- Using the bivariate spline tools from SciPy/FITPACK [8, 9] to simultaneously smooth in space and time.
- No attempt has yet been made to account for sawteeth.
- Using a weighted least-squares smoothing spline with explicitly specified knots.
  - Weighting by $1/\sigma_{T_e}$ mitigates probable outliers.
  - Explicit specification of knots allows capture of fine features while still keeping the rest of the profile smooth.
- Testing so far has been on TS L-mode core T_e profiles.





Bivariate spline smooths in both space *and* time, in contrast to approaches that fit one time-slice at a time.



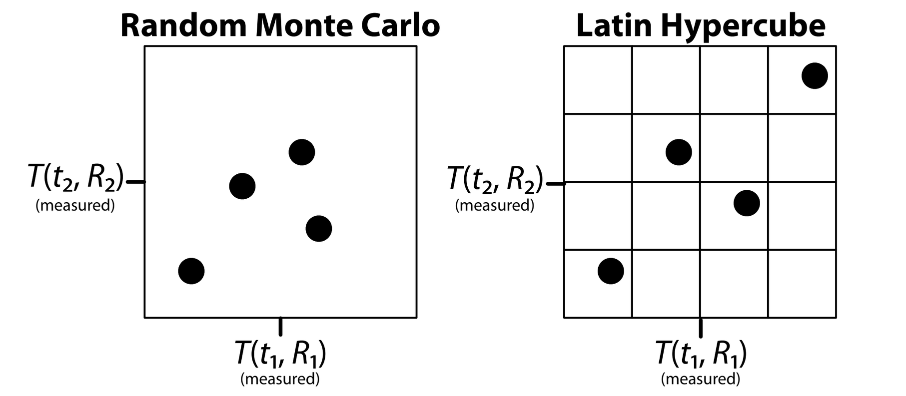
The spline allows the use of a nonuniform spatial grid, handles the change of the TS mid-plane mapping in time.

Work has begun on systematic application of uncertainty quantification

- **Initial goal:** assess UQ methods and tools applied to *profile smoothing/fitting*, obtain error estimates for the gradients.
- **Next step:** apply to other analysis steps throughout the simulation validation pipeline, such as TRANSP and STRAHL.
- Work to date has focused on random sampling techniques using the DAKOTA framework [10]:
  - Supports both Monte Carlo and Latin hypercube sampling.
  - Supports generalized polynomial chaos expansion.
  - Bayesian UQ methods are under development.

Two types of sampling have been investigated

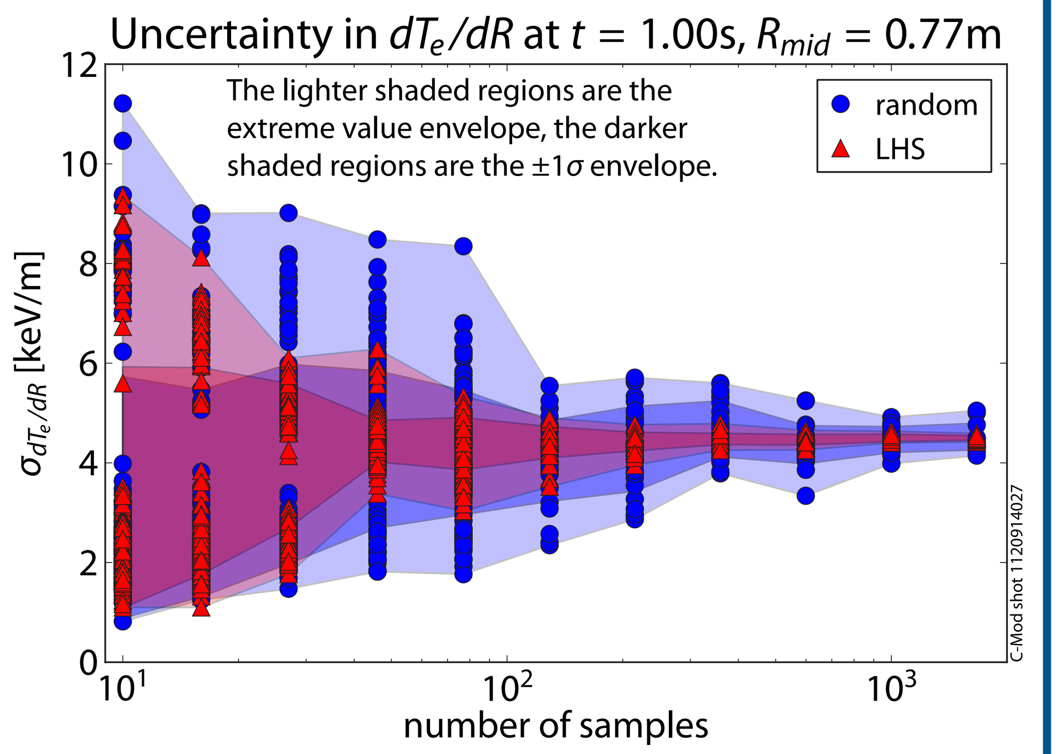
- Monte Carlo sampling randomly samples the uncertain input parameters according only to their probability distributions.
- Latin hypercube sampling (LHS) first divides the domain of each quantity into equal probability cells.
- Then, random samples are placed such that there is exactly one sample in any given cell for any given input.
- This ensures that any given input variable has its complete domain sampled [11, 12].

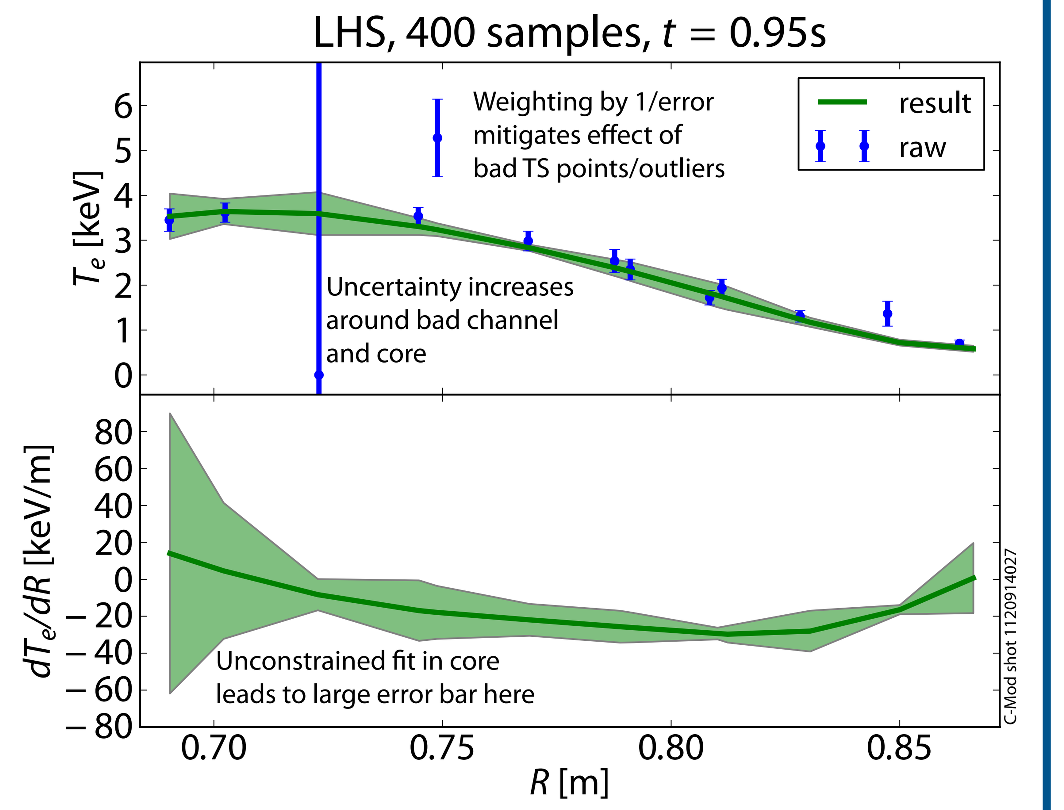


Future work

- Refine fitting algorithm:
  - Incorporate data from other diagnostics.
  - Attempt to handle sawteeth.
  - Constrain behavior at ends of fit.
- Explore effect of errors in magnetic reconstruction.
- Explore additional UQ techniques.
- Apply UQ to other steps in simulation pipeline.

LHS shows up to 10x faster convergence for profile fitting task





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