Explaining Cold-Pulse Dynamics in Tokamak Plasmas using Local Turbulent Transport Models

Pablo Rodriguez-Fernandez*

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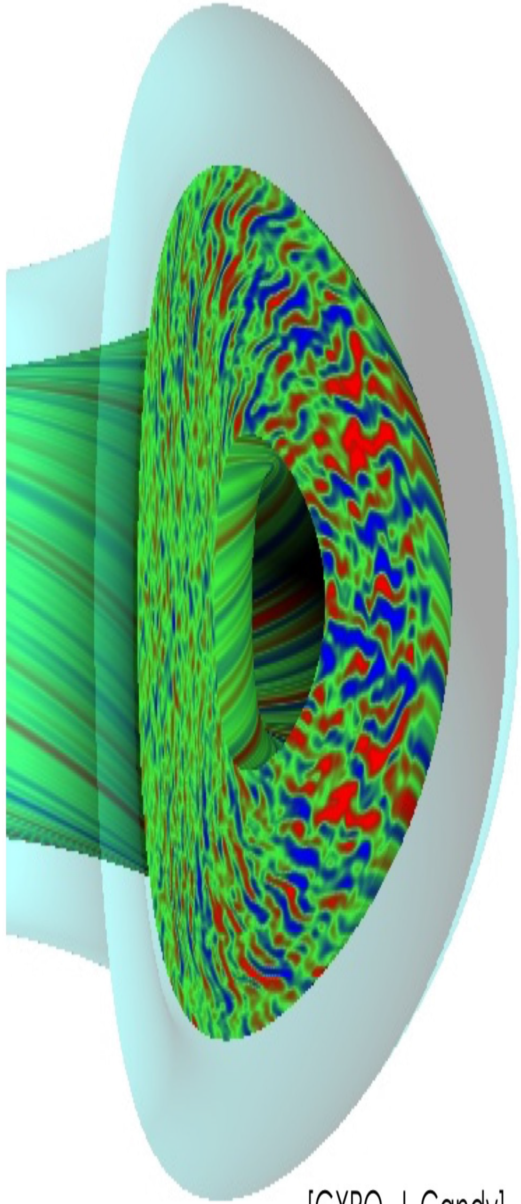
Predicting core plasma performance is critical to design, build and operate fusion reactors

- **Core transport** in tokamaks dominated by turbulence.

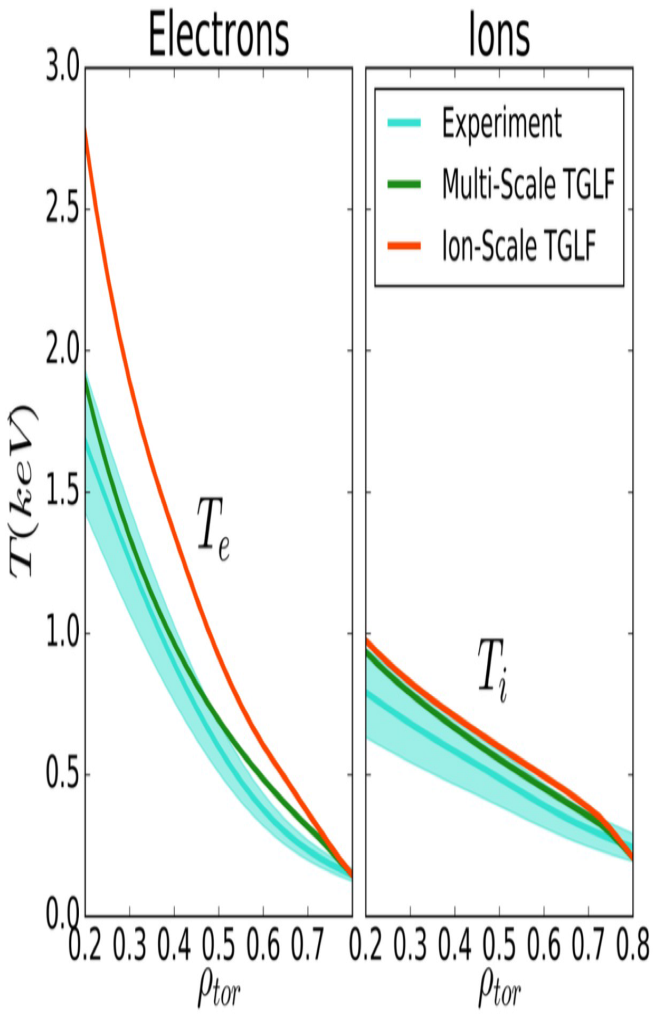


[GYRO, J. Candy]

Predicting core plasma performance is critical to design, build and operate fusion reactors

- **Core transport** in tokamaks dominated by turbulence.
- Many studies are performed to **validate** transport models in steady state.

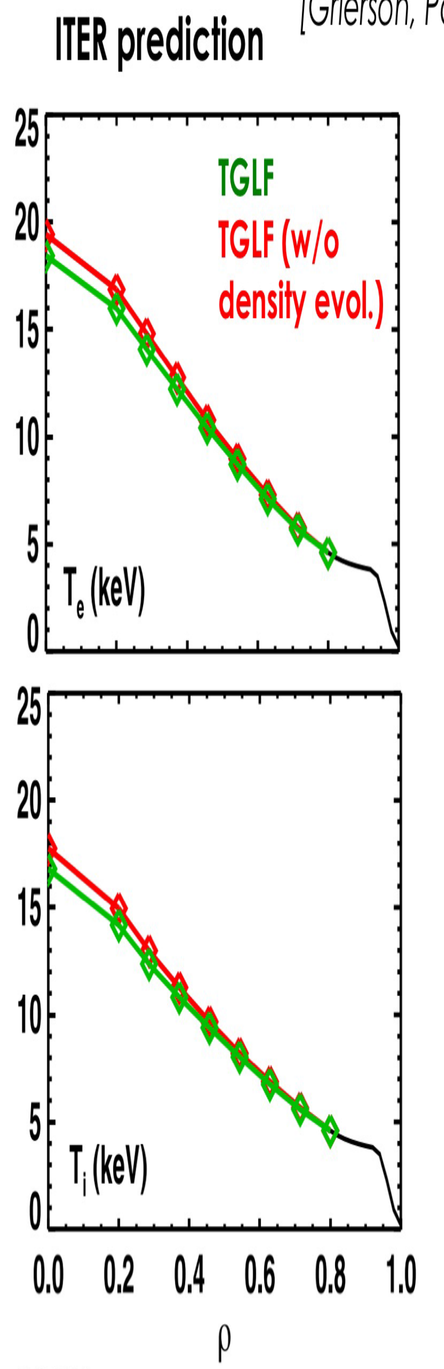
[A. Creely, EPS 2018]



Predicting core plasma performance is critical to design, build and operate fusion reactors

- **Core transport** in tokamaks dominated by turbulence.
- Many studies are performed to **validate** transport models in steady state.
- Predictions for burning plasmas are being made with present models.

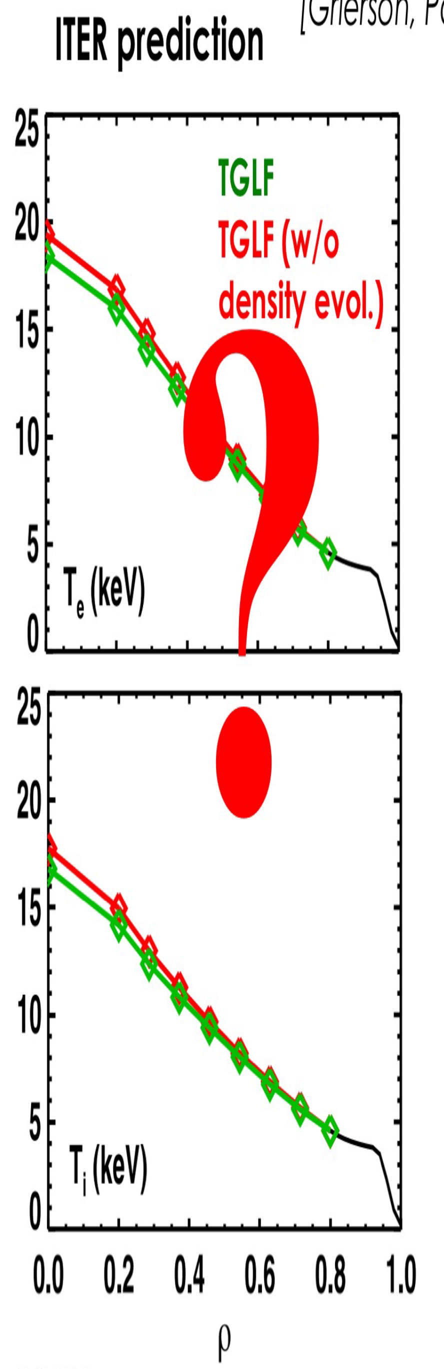
[Grierson, PoP '18]



Predicting core plasma performance is critical to design, build and operate fusion reactors

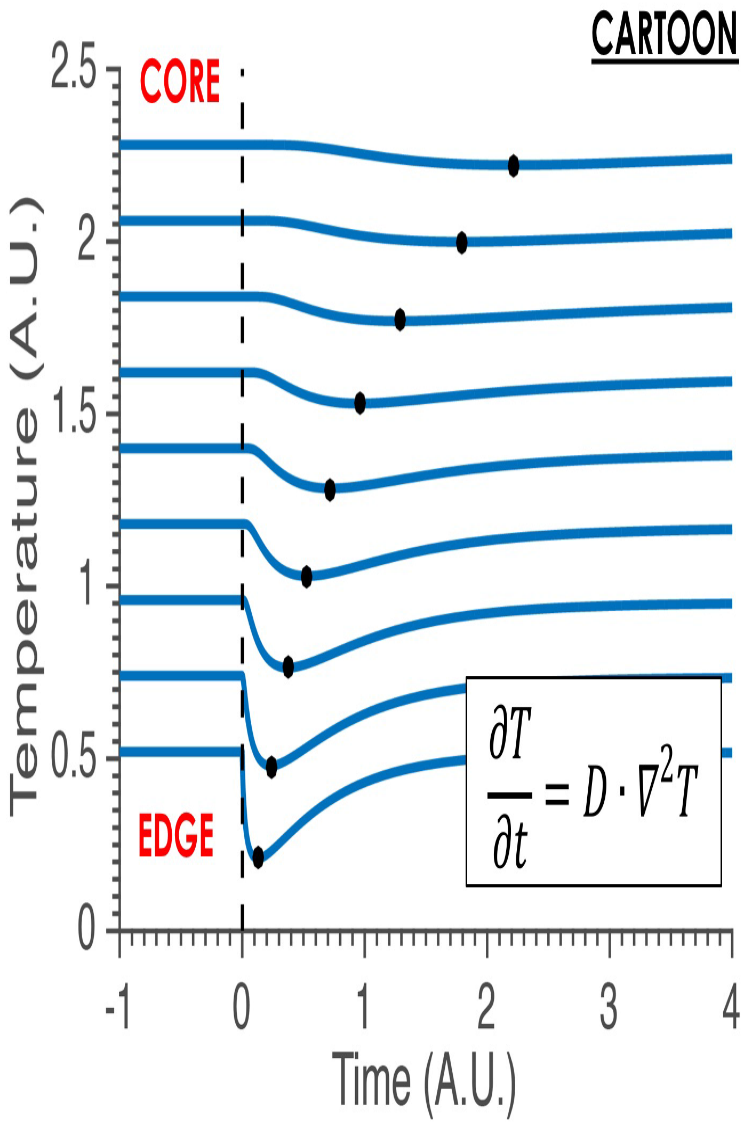
- **Core transport** in tokamaks dominated by turbulence.
- Many studies are performed to **validate** transport models in steady state.
- Predictions for burning plasmas are being made with present models.
- However, some experiments (e.g. cold-pulses) **call the models into question**.
- If models cannot capture behavior in present experiments, *why should we trust them for predictions in future devices?*

[Grierson, PoP '18]



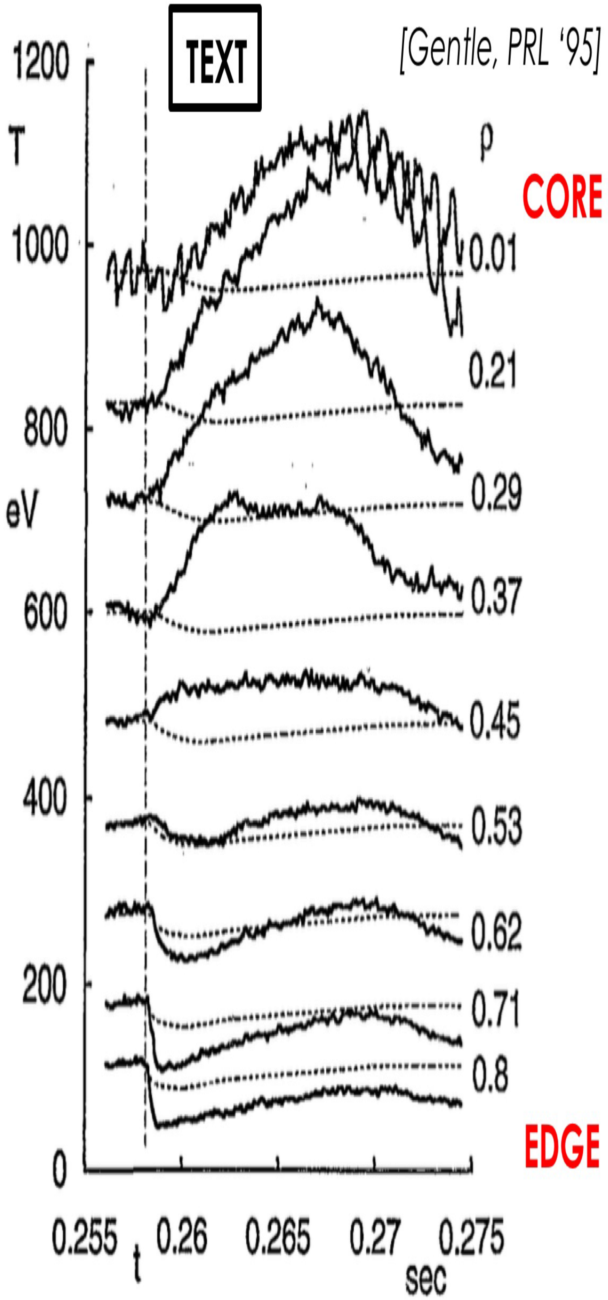
Transient transport can be tested as an edge cold pulse travels to plasma core

- In cold-pulse experiments, **edge temperature drops** and transient transport is studied as perturbation travels to core.
- **Expected response** (modeled by diffusion):
  - Delay in time
  - Decreasing in amplitude.



Cold-pulse experiment is a classical example of the so-called "nonlocal" transport

- Cold-pulse experiments show counter-example to diffusive, local transport
- At low collisionality, **core temperature rapidly rises** after edge cold-pulse injection.
- Past work referred to these phenomena as "non-local" transport events.



Why should we care about cold-pulse propagation?

- Observed in >10 machines, both tokamaks and stellarators.
- No explanation based on local physics has been found so far that match experiments.
- Featured as nonlocal transport and validation challenge in review articles.

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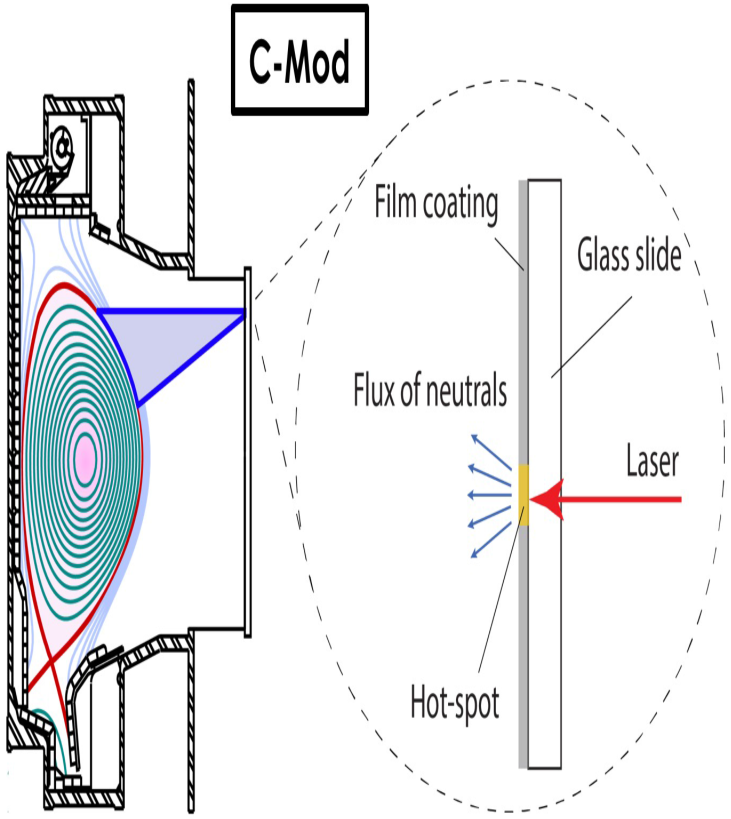
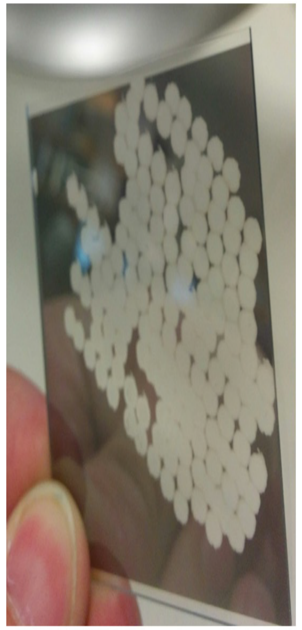
> - Review article on nonlocal transport *[Ida NF '15]*:
>
>   "[...]the violation of the familiar local expression **compels us to explore new approaches** to the predictive modelling for burning plasmas."
>
> - ITER transport physics basis paper *[Doyle NF '07]*:
>
>   *"[...]The observed fast radial propagation of the pulses from the plasma edge to the core has been a **challenge** to be explained by local diffusive transport models."*

Transient transport is studied using perturbative cold-pulse injections with Laser Blow-Off

- **Edge cold-pulses** are injected using laser blow-off (LBO) technique.

- Laser pulse ablates coating in glass slide, resulting in flux of neutrals to plasma.





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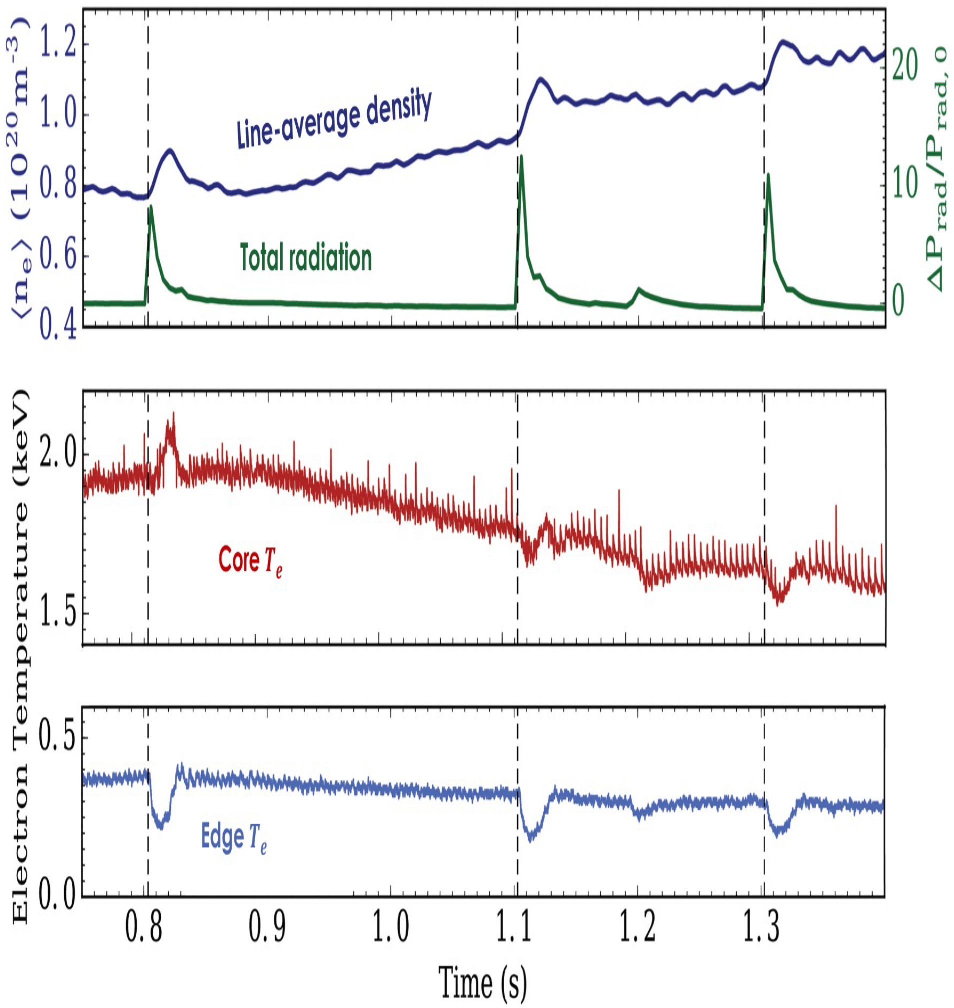
- **Edge cold-pulses** are injected using laser blow-off (LBO) technique.

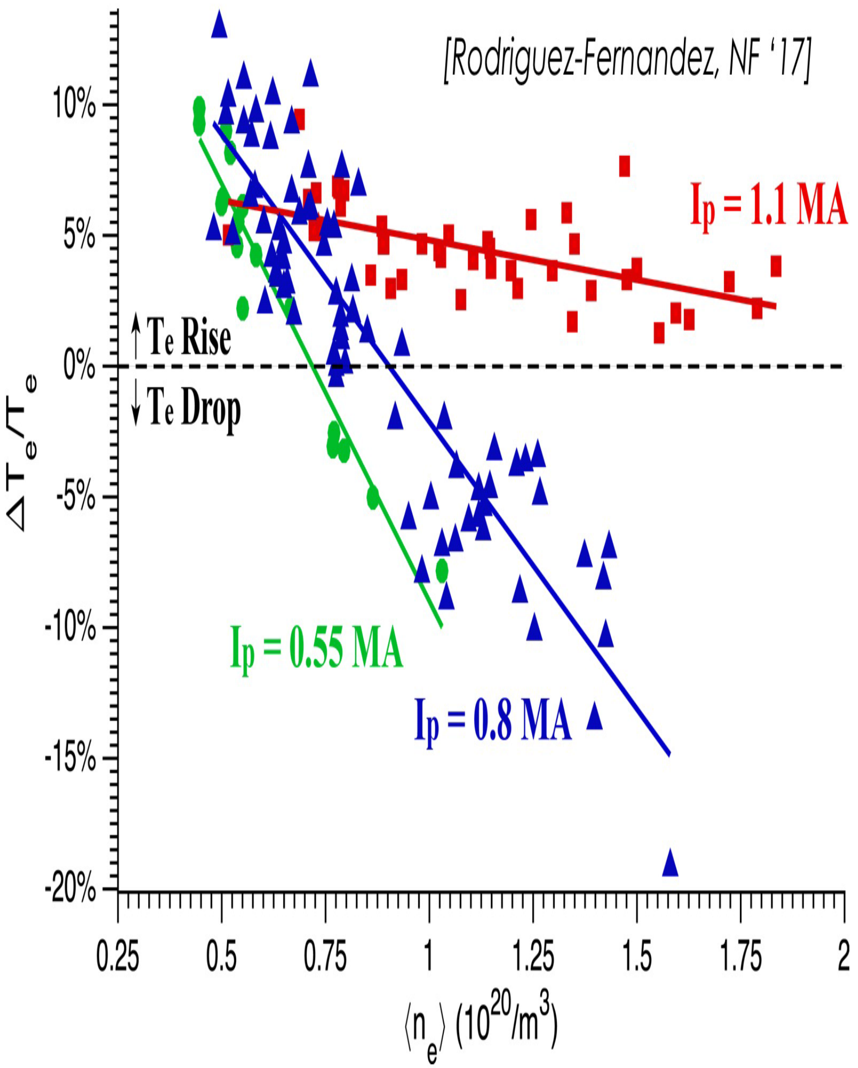
- Laser pulse ablates coating in glass slide, resulting in flux of neutrals to plasma.

- As a consequence:
  - Radiation sink → ΔP_{rad}
  - Density "bump" → Δn_e (& ΔZ_{eff})



Strong effect of density and current on temperature inversions is observed experimentally

- Temperature inversions get **weaker as density increases**, and eventually disappear.
- Temperature inversions **return at high-density with high-current**.
- Transition coincides with *intrinsic rotation reversal density* for most Ohmic plasmas.



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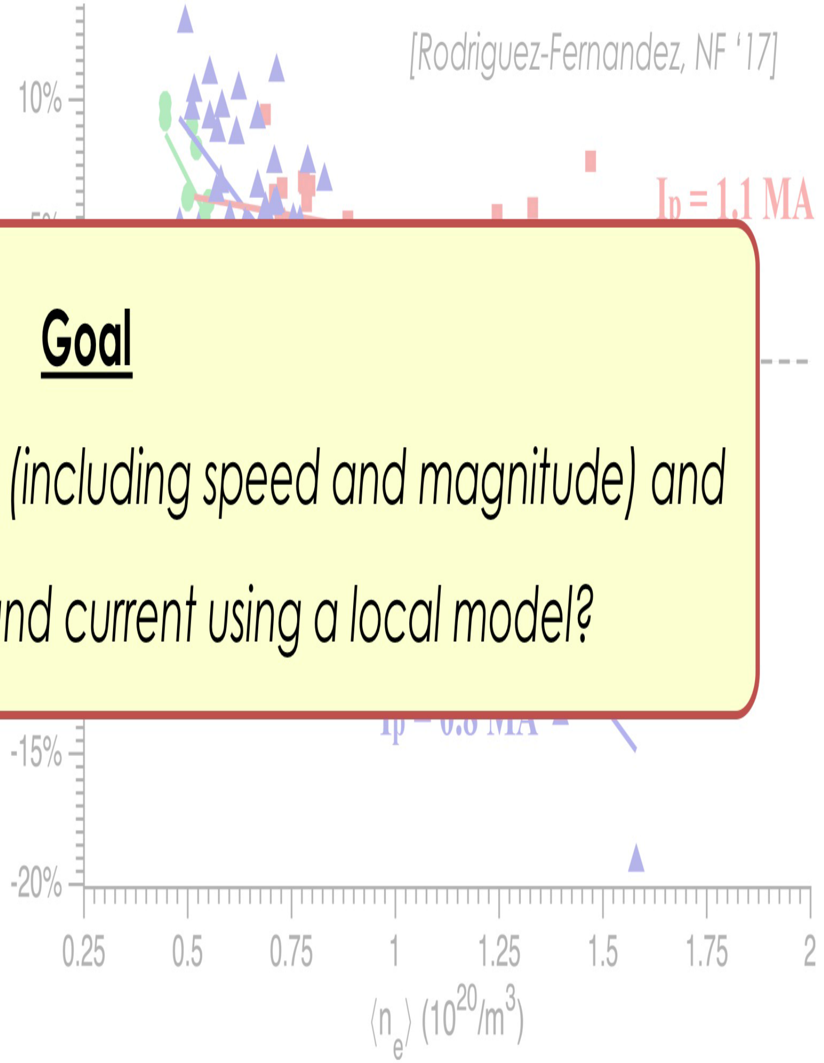

Goal

Can we reproduce this effect (including speed and magnitude) and its trends with density and current using a local model?

Integrated modeling of perturbative transport phenomena performed using TRANSP+TGLF

- Plasma evolution modeled with fluid-like (TRANSP).

$$\frac{3}{2}\frac{\partial}{\partial t}\left(n_e T_e\right) = -\nabla \cdot \left(\mathbf{q}_e + \frac{5}{2} T_e n_e \mathbf{u}_e\right) - Q_{ie} - \mathbf{u}_i \cdot \nabla\left(n_i T_i\right) + \hat{Q}_e$$

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* *Staebler, NF '17*

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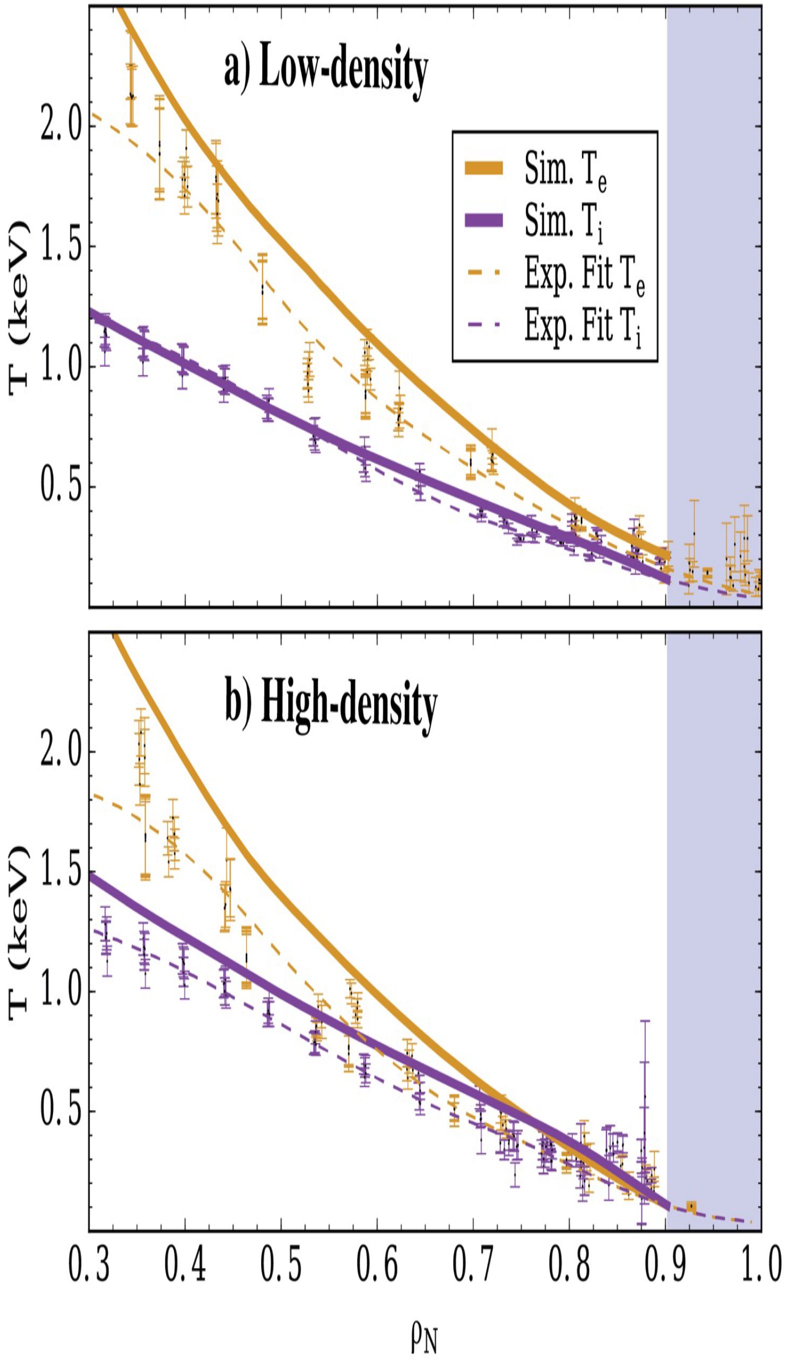
- **TGLF-SAT1** is a quasilinear model with a saturation rule that is fitted to a database of nonlinear GYRO simulations (including multiscale). This leads to:
  - Nonlinear upshift of critical gradient, (∇T_{crit}).
  - Higher "stiffness", as captured by incremental thermal diffusivity (χ^{inc}).
  - Amplification of Trapped Electron Mode driven transport (TEM).

* *Staebler, NF '17*

MIT PSFC Alcator C-Mod

Ion and electron temperatures are evolved until reaching steady-state in the simulation

- Before perturbing P_{rad} and n_e, **steady-state** is reached in the simulation.
- Boundary conditions for T_e and T_i are chosen at $\rho_N = 0.9$.
- Predicted profiles close to experimental values (within 2σ).
- Turbulent and neoclassical transport as predicted.



Alcator C-Mod

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Integrated modeling of perturbative transport phenomena performed using TRANSP+TGLF

Sources/Sinks

- Plasma evolution modeled with fluid-like (TRANSP).

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- Turbulent transport given by TGLF-SAT1 model.

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- Radiation sink ➔ Changes in **source term**:

$$\hat{Q}_e = P_{OH} - P_{rad}$$

MIT PSFC Alcator C-Mod

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Transport — Sources/Sinks

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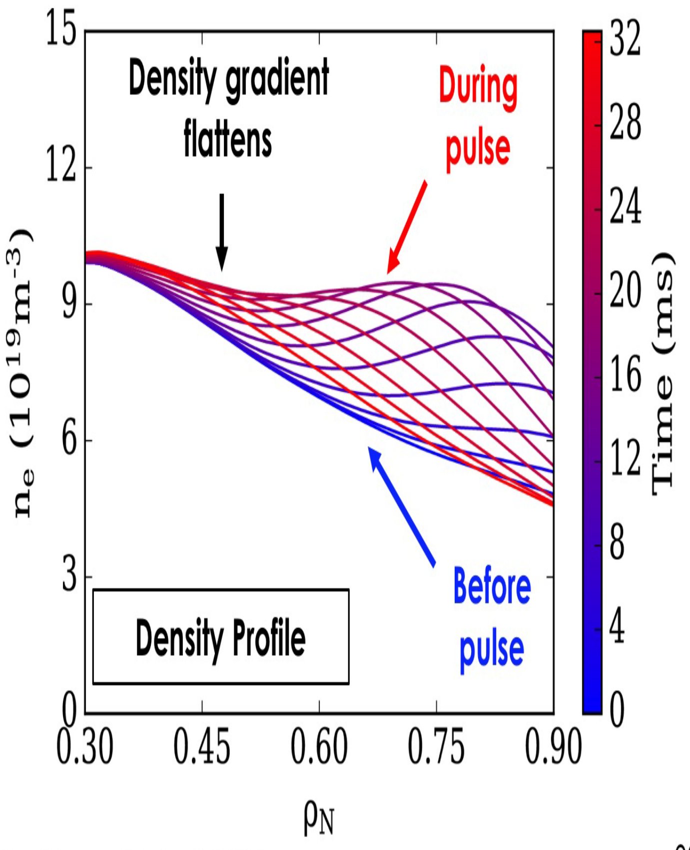
- Radiation sink ➔ Changes in source term:

$$\hat{Q}_e = P_{OH} - P_{rad}$$

- Density pulse leads to change in density gradients ➔ Effect in transport.

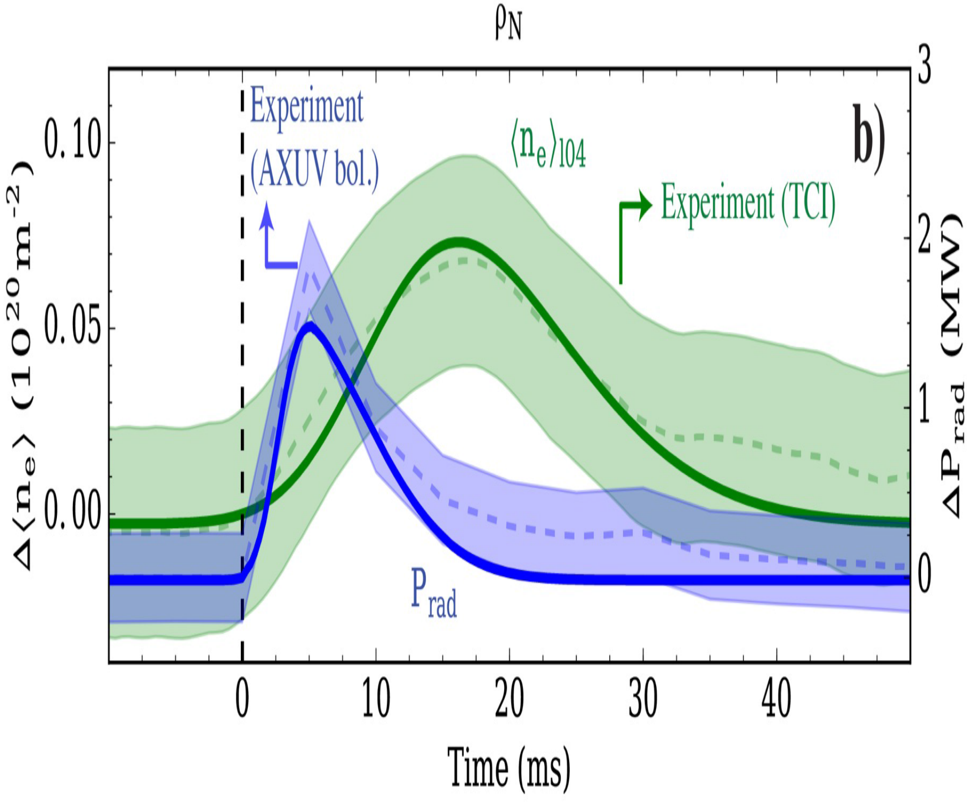


Experimentally-constrained model of LBO injection is introduced in the simulations

- Radiative losses and density profiles were not available in high time resolution.
- We made an educated guess: experimentally-constrained Gaussian pulses.

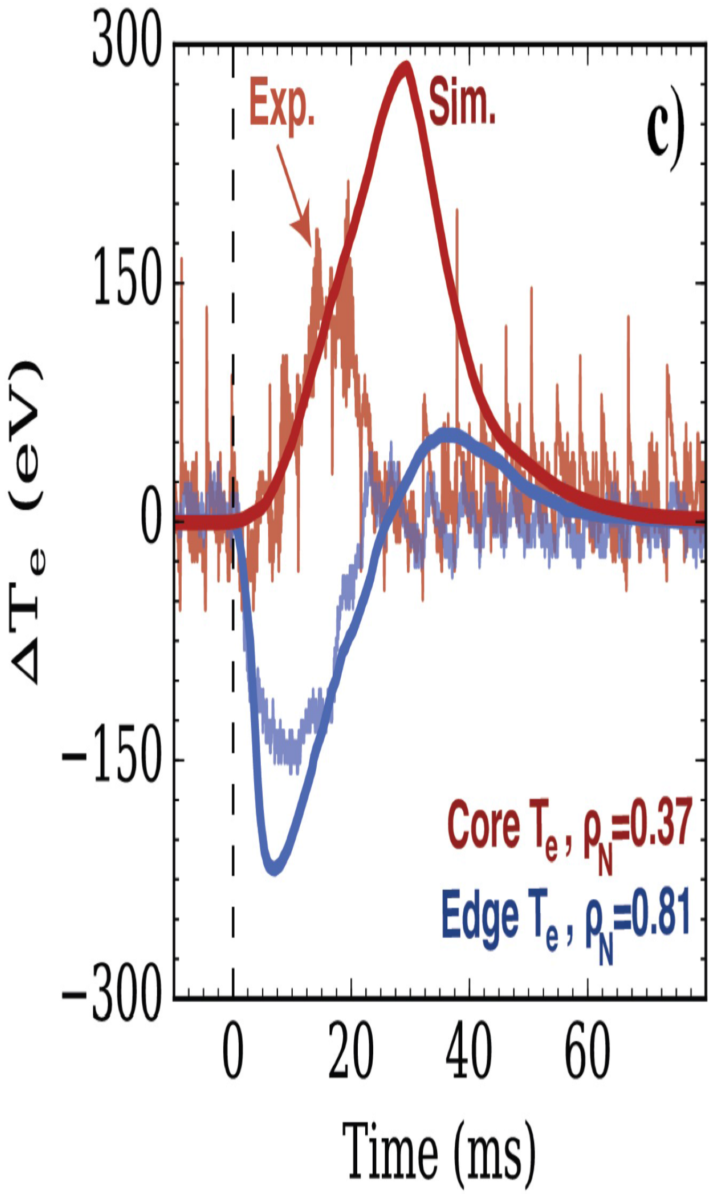
➢ Edge radiation sink constrained by **total radiative power** (bolometers).

➢ Density perturbation constrained by **line-average density** (interferometers).

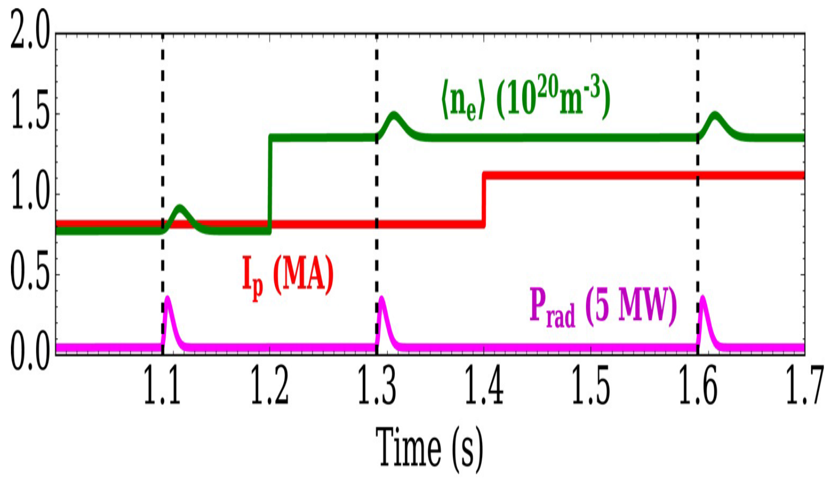


Core T_e inversions following edge cold-pulses appeared spontaneously in the low density condition

- Electron and ion temperatures are allowed to evolve self-consistently.
- Core T_e **promptly increases** at low density following edge T_e drop.



Simulations with variations of density and plasma current show that trends are captured by the model



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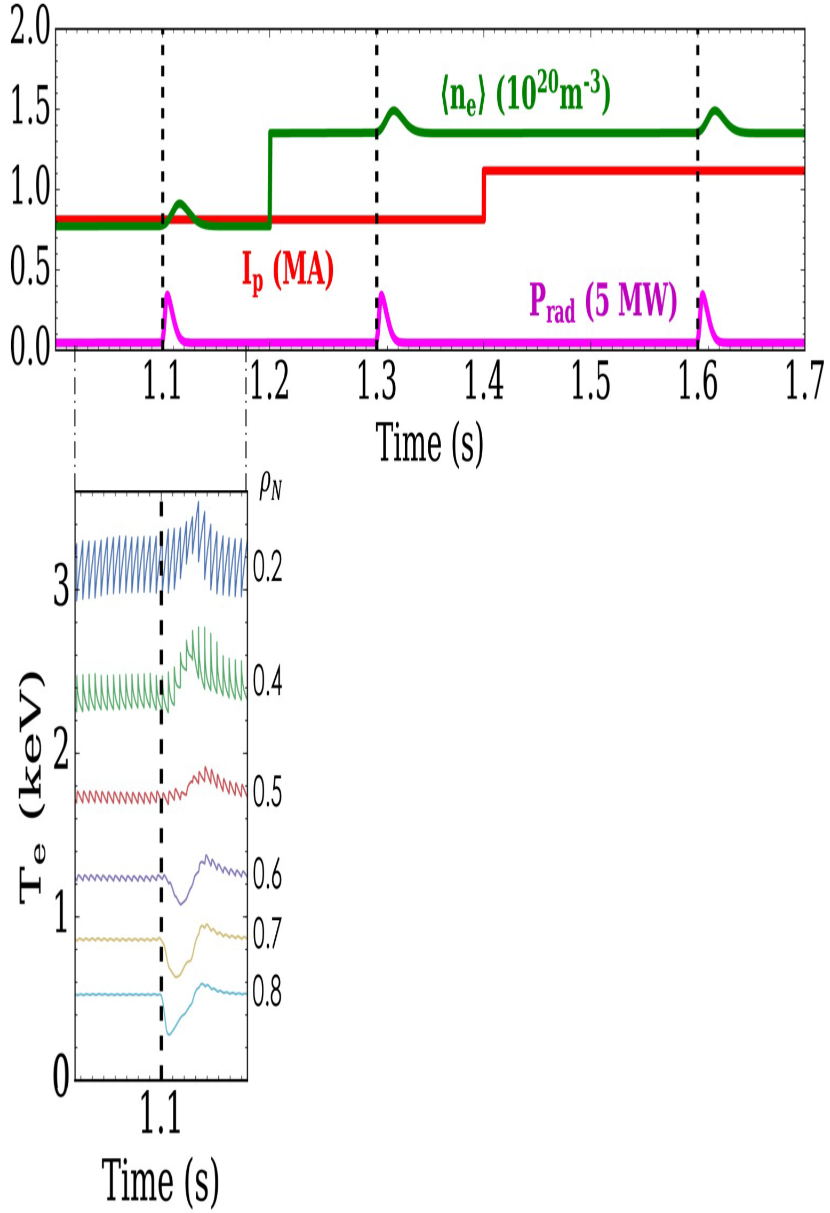
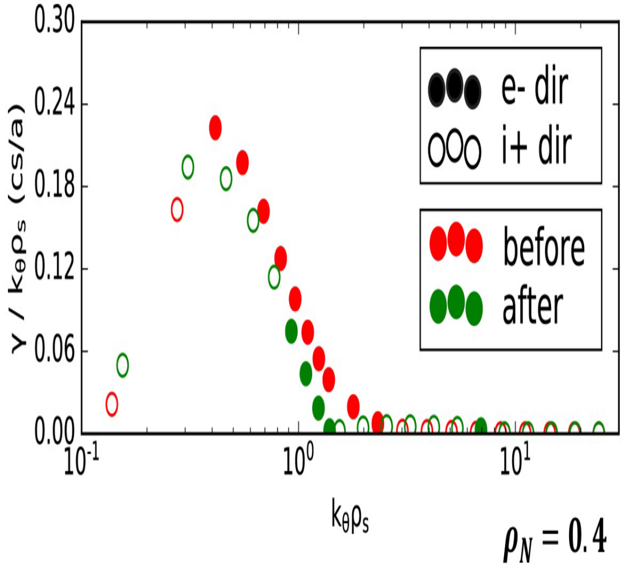


1. **<u>Low density</u>** simulation exhibits core temperature increase.
   - ➢ TEMs are stabilized by the arrival of density pulse ➔ Less transport.



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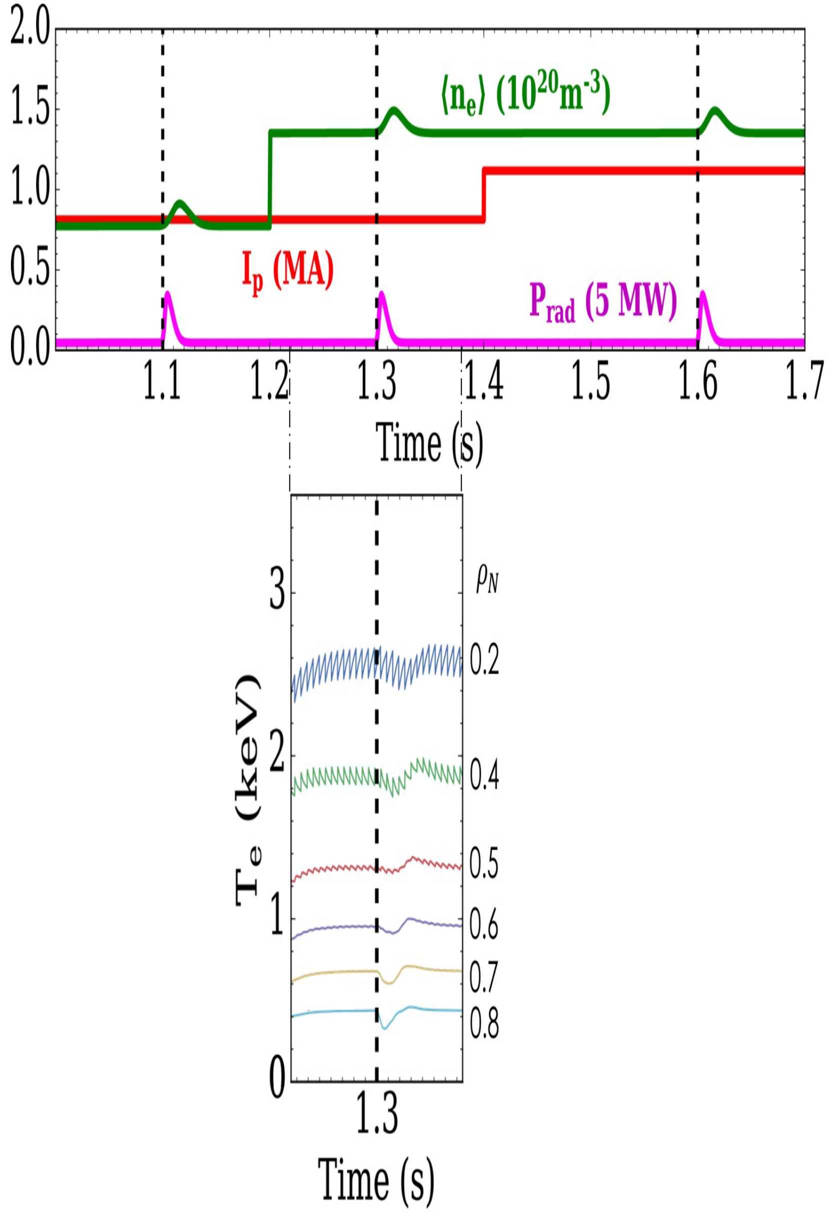
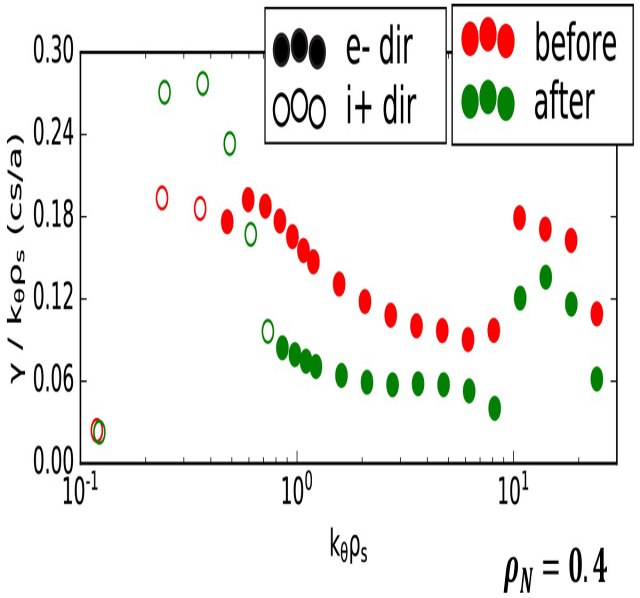


2. **Increase in density** makes core effect disappear.
   - TEMs are stabilized, but ITGs become more unstable ➔ More transport.



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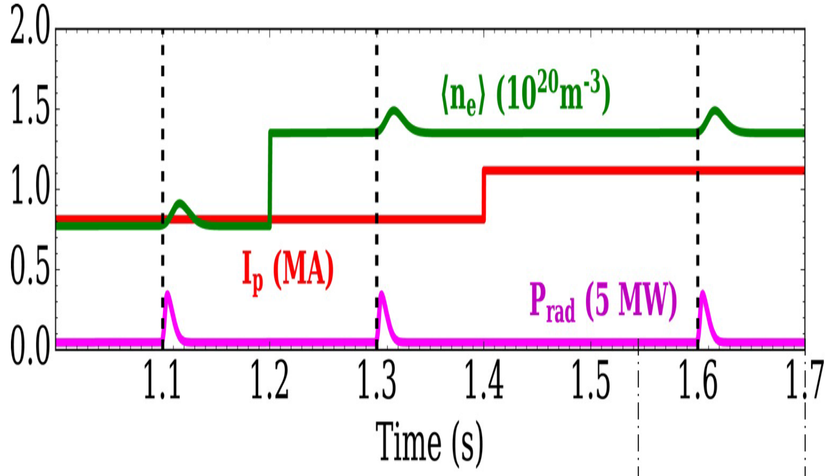
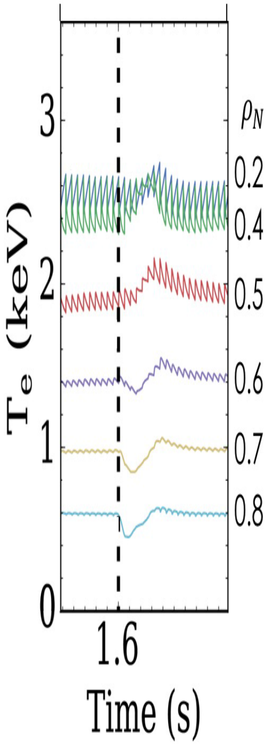
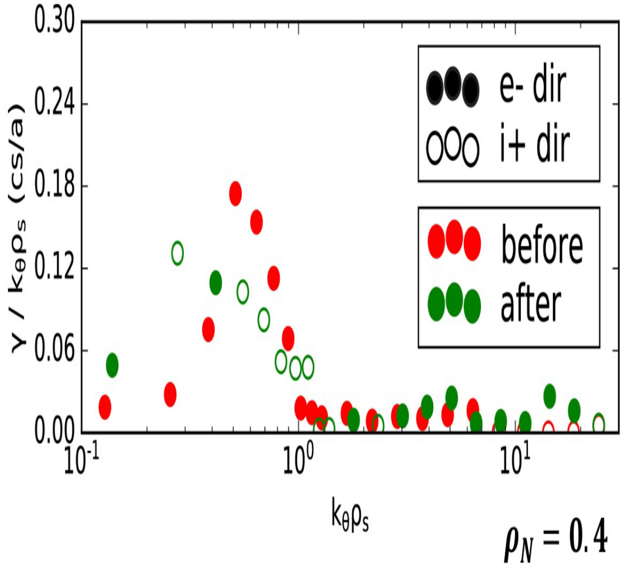
Simulations with variations of density and plasma current show that trends are captured by the model

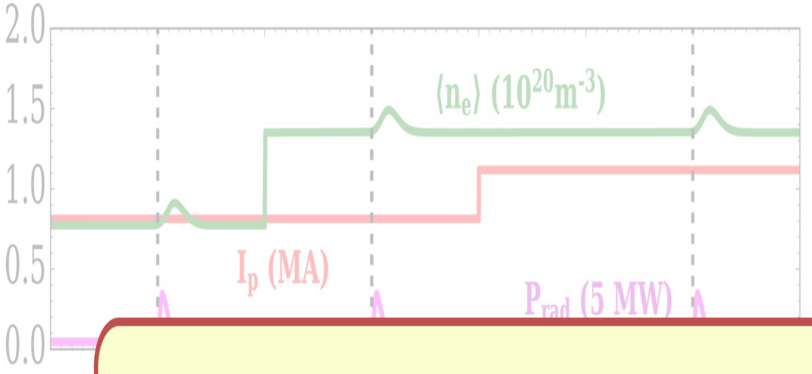


3. **Increase in current** makes core effect appear again.
   - TEMs are stabilized ➔ Less transport.





Simulations with variations of density and plasma current show that trends are captured by the model

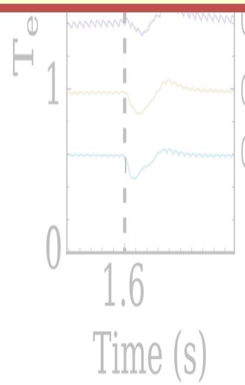


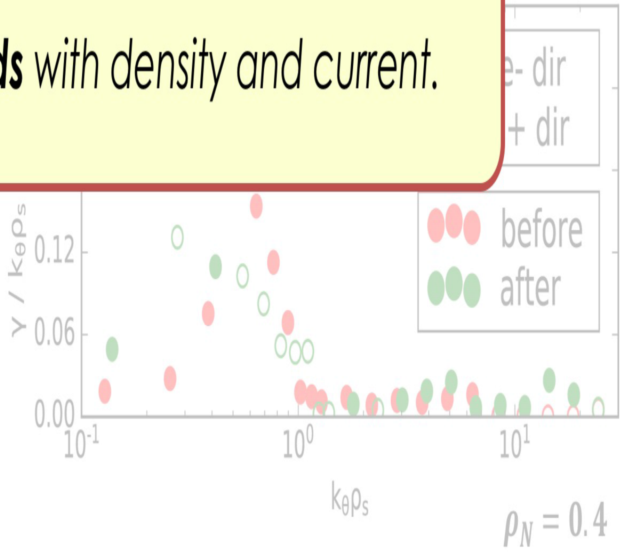
3. <u>Increase in current</u> makes core effect appear again.

   ➢ TEMs are stabilized ➔ Less

<u>Conclusion</u>

TGLF-SAT1 local model captures ***temperature inversion*** *(experimentally-relevant magnitude and speed) and* ***trends*** *with density and current.*





Main message: Nonlocal effects are not needed to capture cold-pulse phenomena in tokamaks plasmas

Summary:

- For 20 years, cold-pulse experiments suggested **missing piece** in transport models.

  [Gentle PRL '95]

- **Dedicated experiments** in C-Mod were designed to isolate cold-pulse phenomenon.

  [Rodriguez-Fernandez NF '17]

- Simulation results from C-Mod show that **local transport models** capture full dynamics.

  [Rodriguez-Fernandez PRL '18]

Future work:

- Experiments in DIII-D to track density pulse propagation with reflectometer.

  [Come see my invited talk at *2018 APS-DPP* **PI2.00003**]

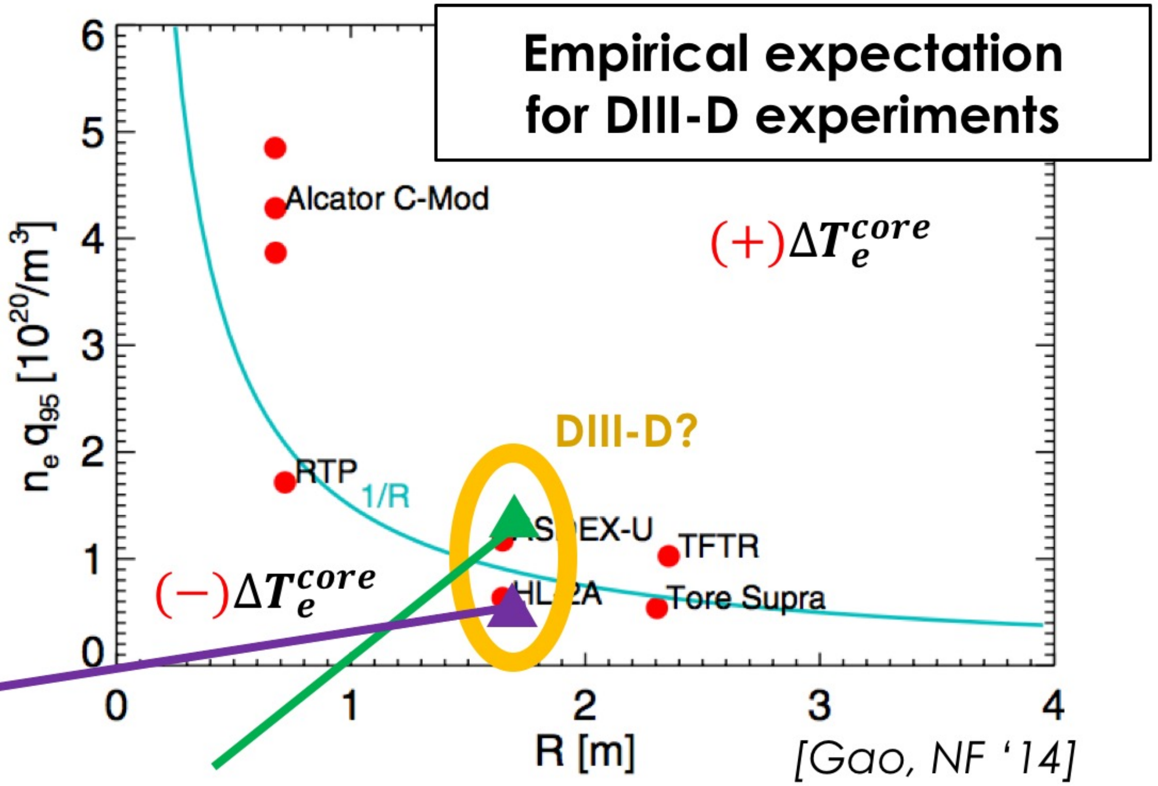
- Self-consistent model for particle transport.

Back-up Slides

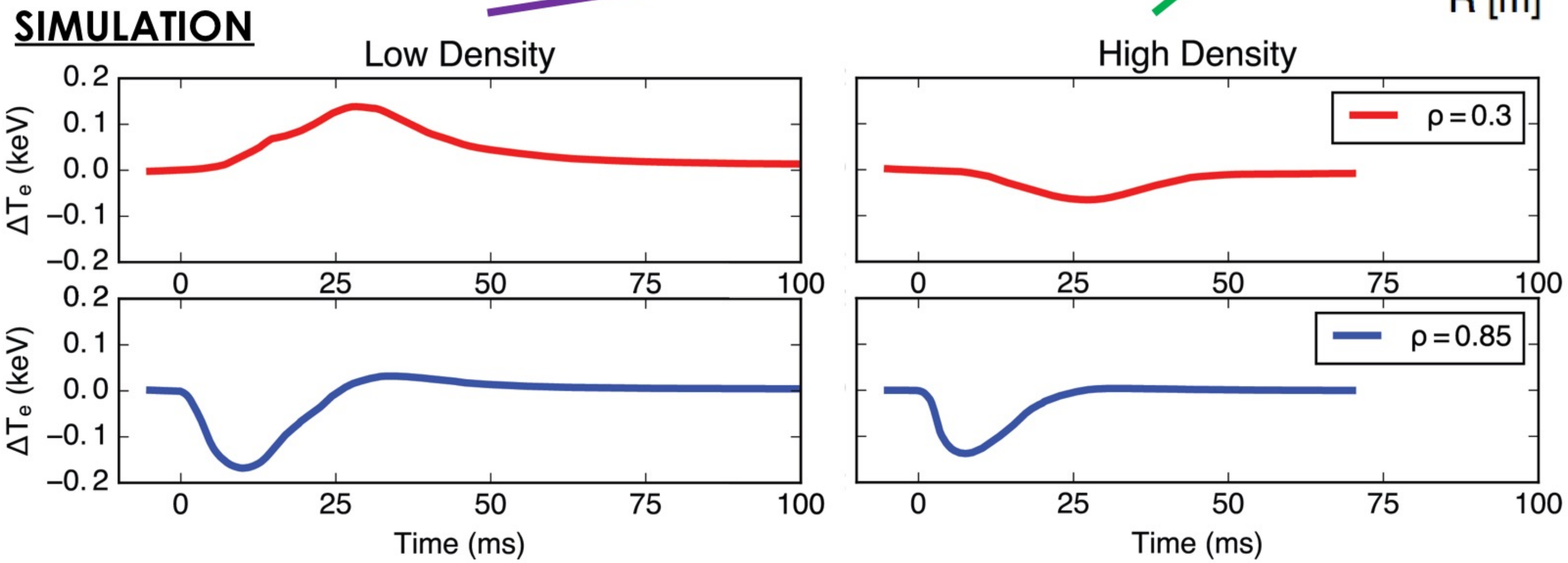
DIII-D Experiments and Modeling

Predictions were performed in DIII-D, where cold-pulses were never reported in the literature

- Empirical scaling with other machines suggests that temperature inversion would happen in DIII-D below $n_{20}q_{95} \sim 1.0 \pm \mathbf{0.5}$
- New predictions using a simplified injection were used to **identify conditions** where temperature inversions occur.

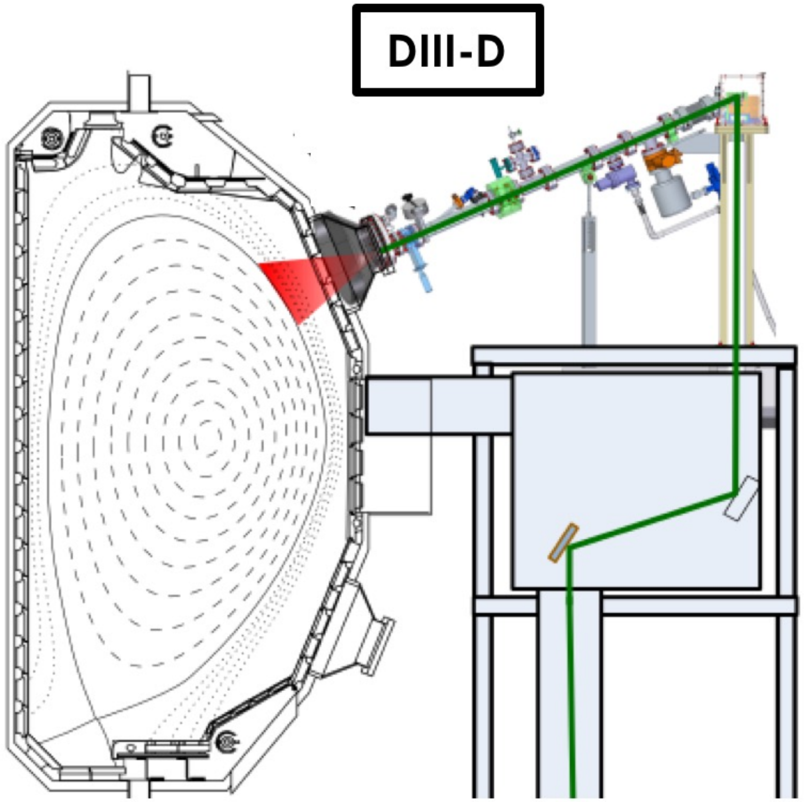


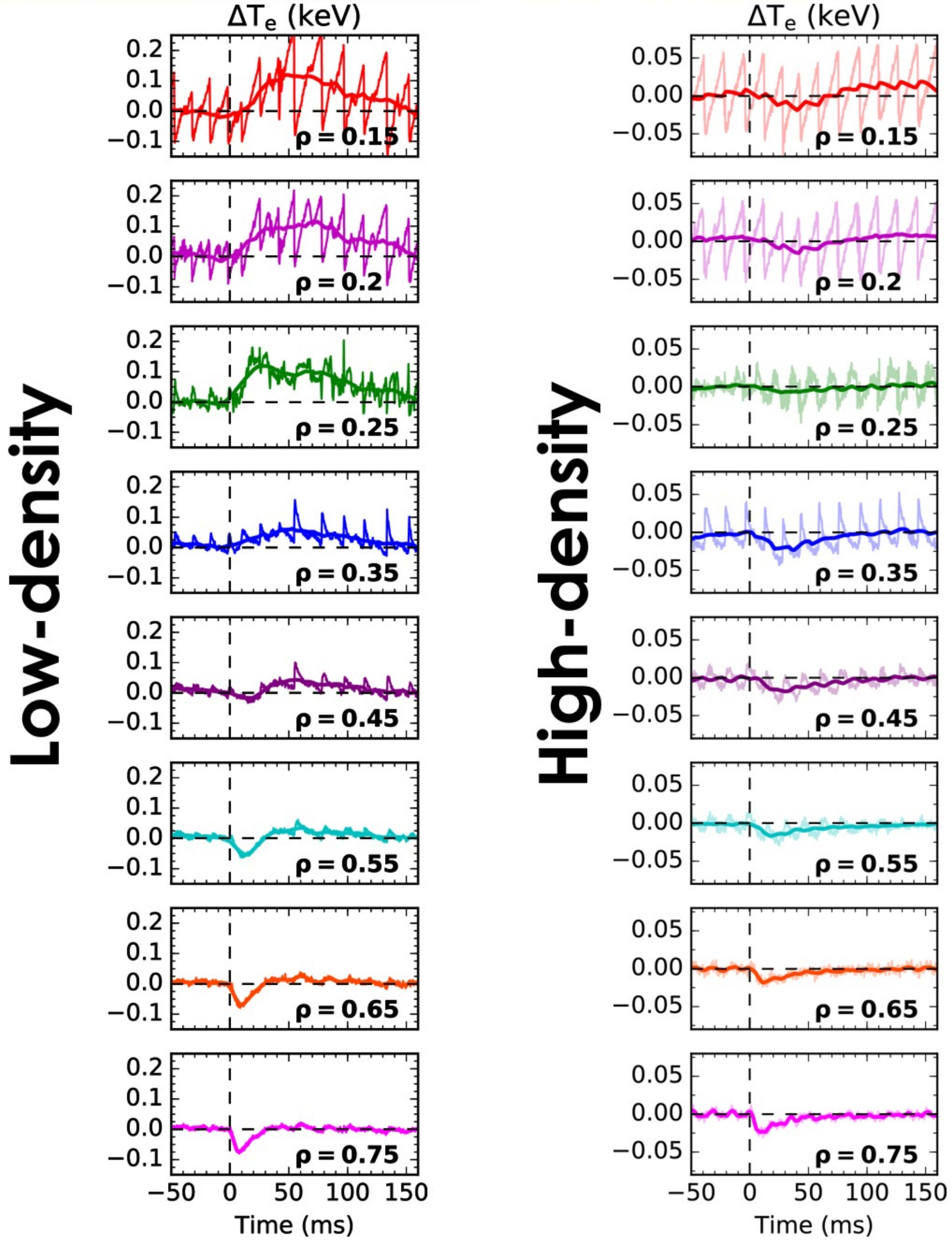
[Gao, NF '14]



New experiments in DIII-D confirm that TGLF predictions capture the 1/R dependence

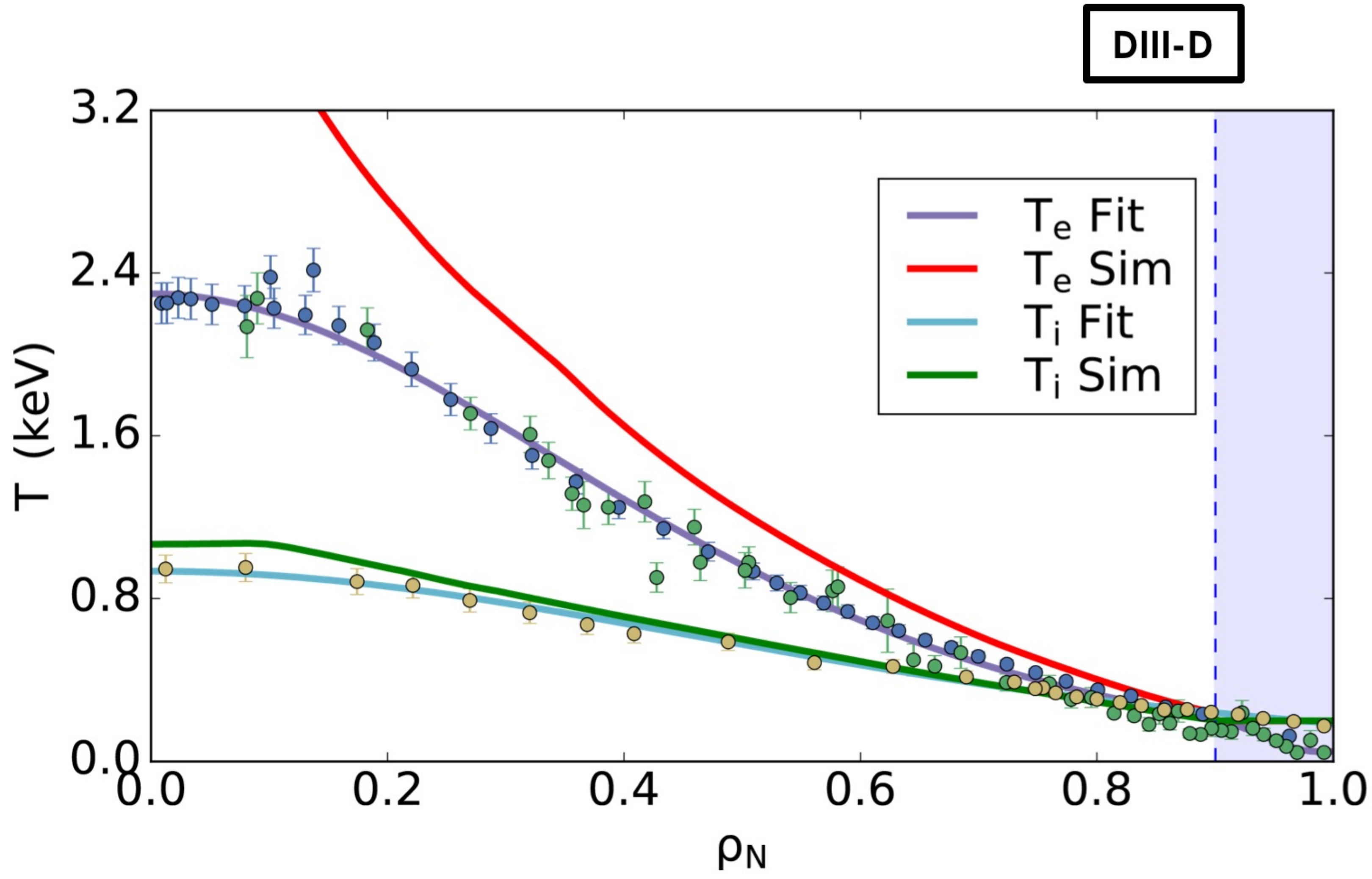
- New LBO is used to introduce cold pulses in DIII-D.
- Temperature inversion occurred at predicted plasma condition.





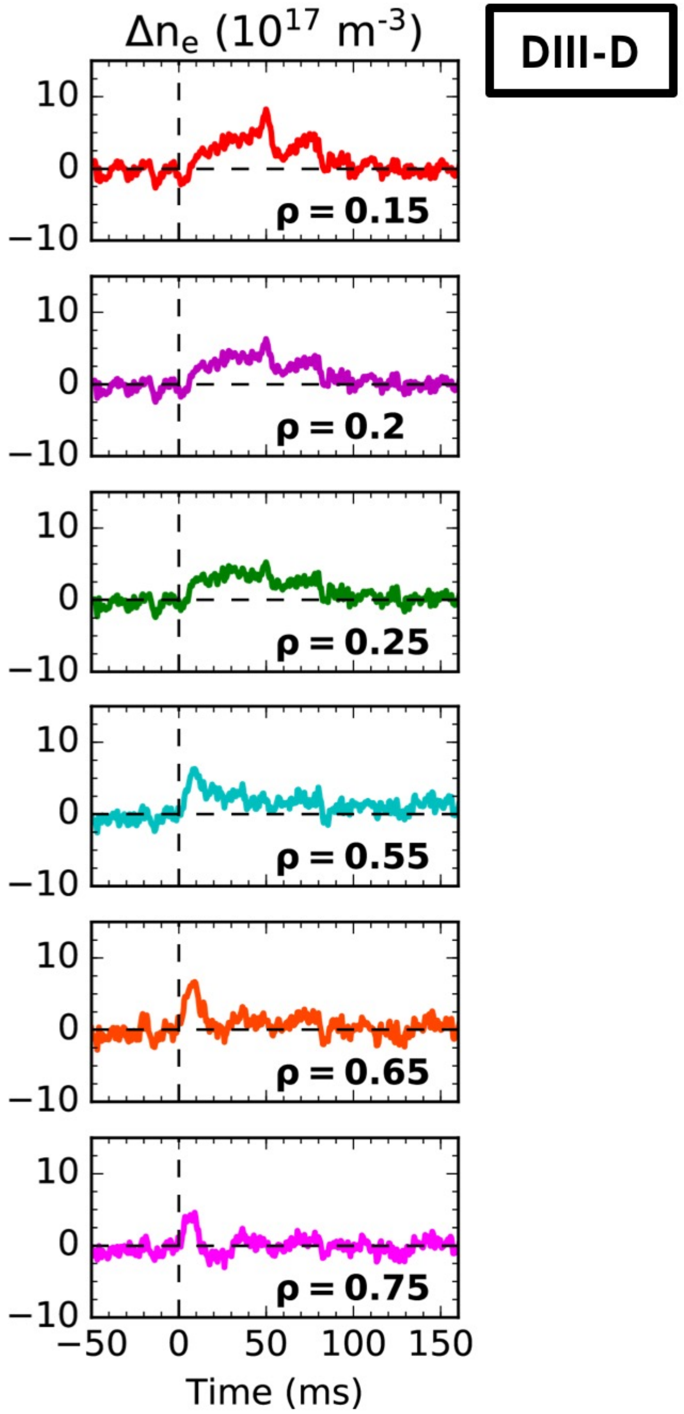
TGLF-SAT1 is used to evolve temperatures to steady-state, revealing underprediction of transport

- Integrated modeling is performed using experimental measurements *(post-diction)*.
- Steady-state in reached in the simulation before the perturbation is introduced.
- Boundary conditions for T_e and T_i are chosen at $\boldsymbol{\rho_N = 0.9}$.
- TGLF-SAT1 strongly **under-predicts core transport** for this low-density Ohmic DIII-D plasma.



Density pulse consistent with reflectometer data is introduced in simulation

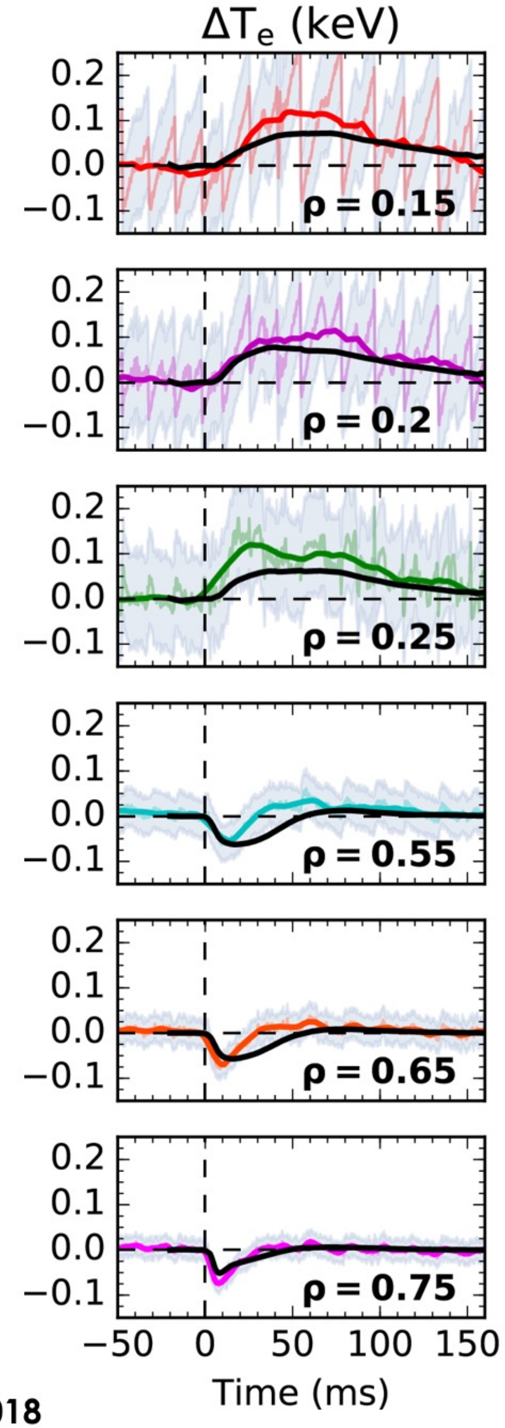
- A **big caveat** in the C-Mod work was the imposed density pulse (constrained only by line-integrated interferometer measurements).
- *Does the density pulse actually move that fast?*
- In DIII-D experiments, we can sort that out thanks to high time resolution **density profile reflectometer**.
- New experiments in DIII-D **confirm a density pulse** that travels quickly.
- Core density pulse with Gaussian shape is fitted to reflectometer data.



Core temperature inversion is reproduced in simulations using experimentally-measured density pulse

- Simulated core temperature traces (**black**) consistent with experiment (**colored**)
- **Disagreements** between simulation and experiments could be linked to the predicted background steady-state profiles.
- Strong over-prediction of steady-state T_e leads to $\boldsymbol{\nabla T_e}$-**driven TEM** turbulence, thus density pulse has less effect than expected for a TEM-dominated plasma.

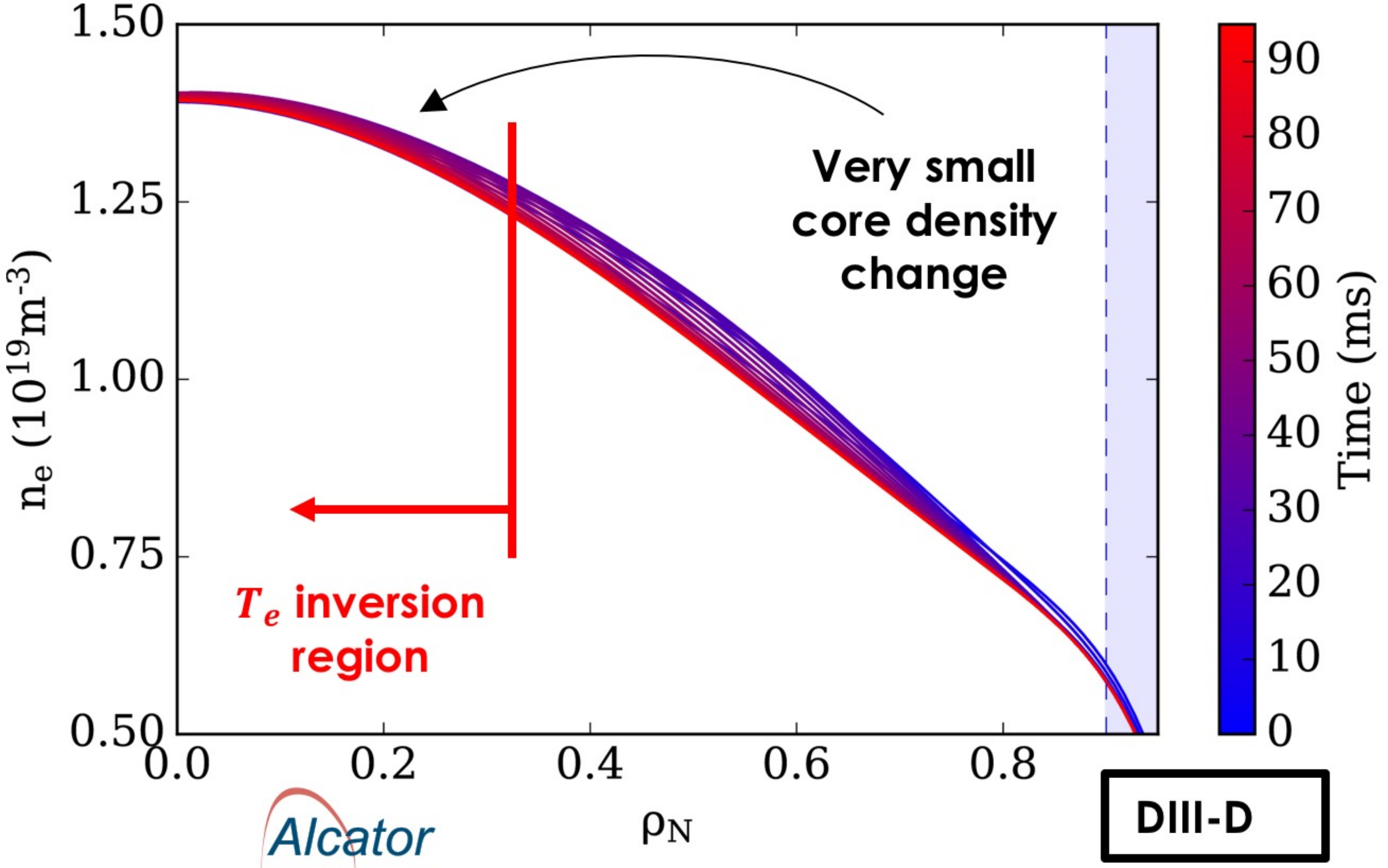
DIII-D



MIT PSFC Alcator C-Mod

Reconciling "nonlocal observations" with local models required high-stiffness of TGLF-SAT1

- Past work referred to these as **nonlocal effects**, as local plasma parameters seemed unchanged before T_e increases.
- **Modest change in density** leads to T_e increase.
- **Change in gradients** (& ν_{ie}, Z_{eff}) provides enough TEM stabilization.



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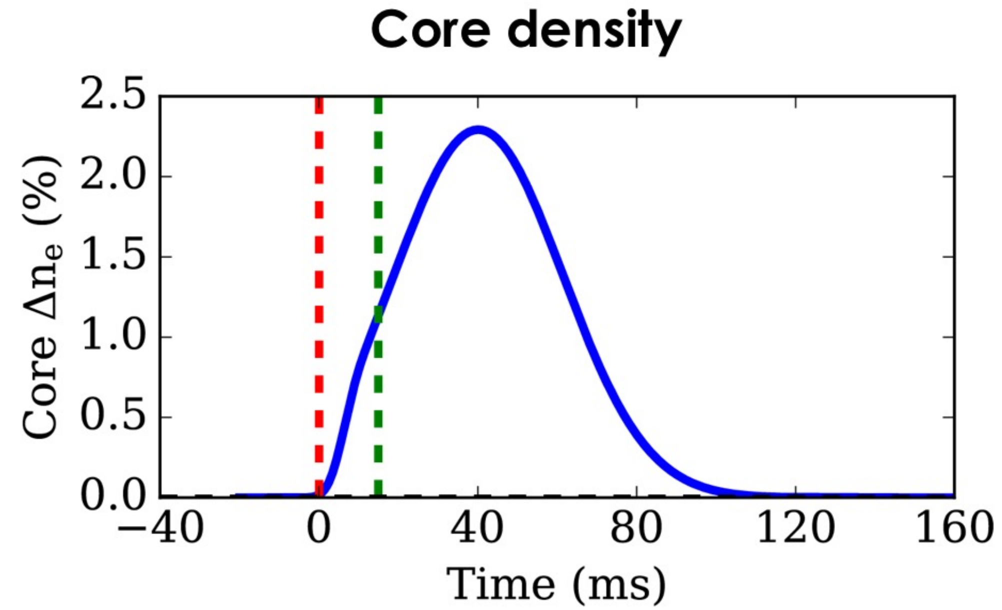

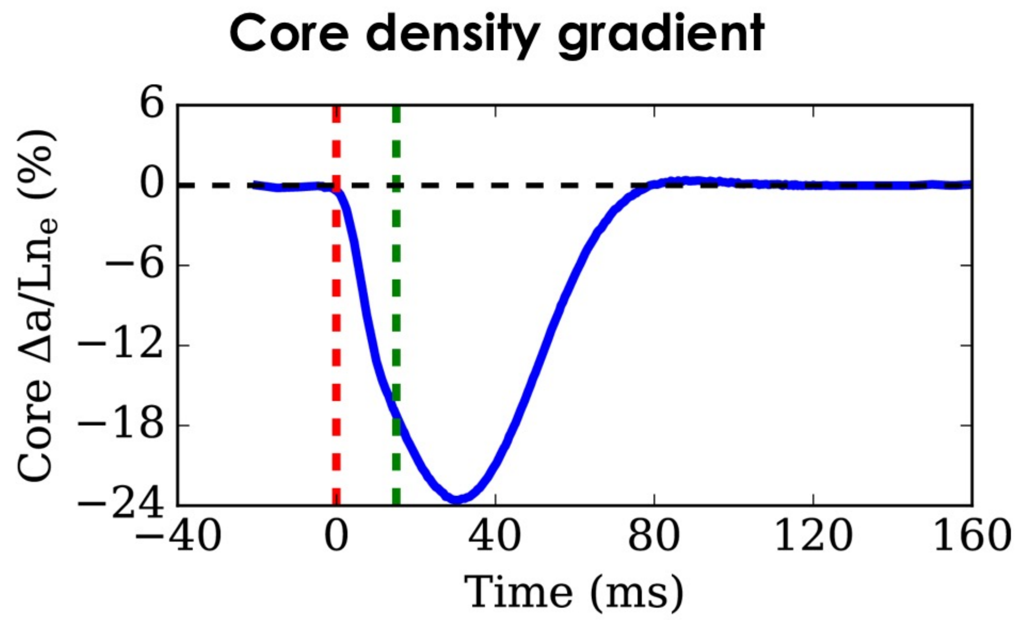

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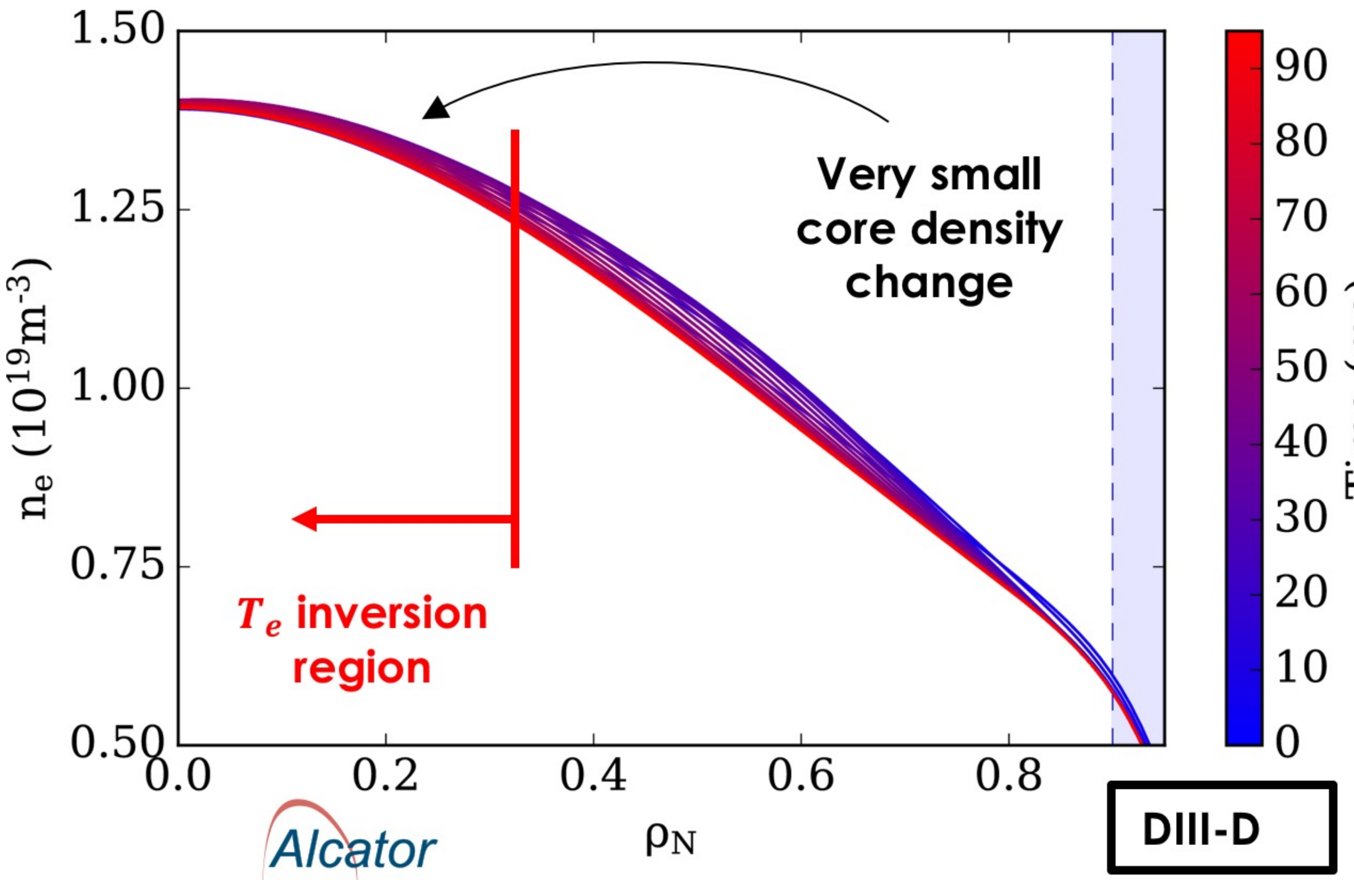
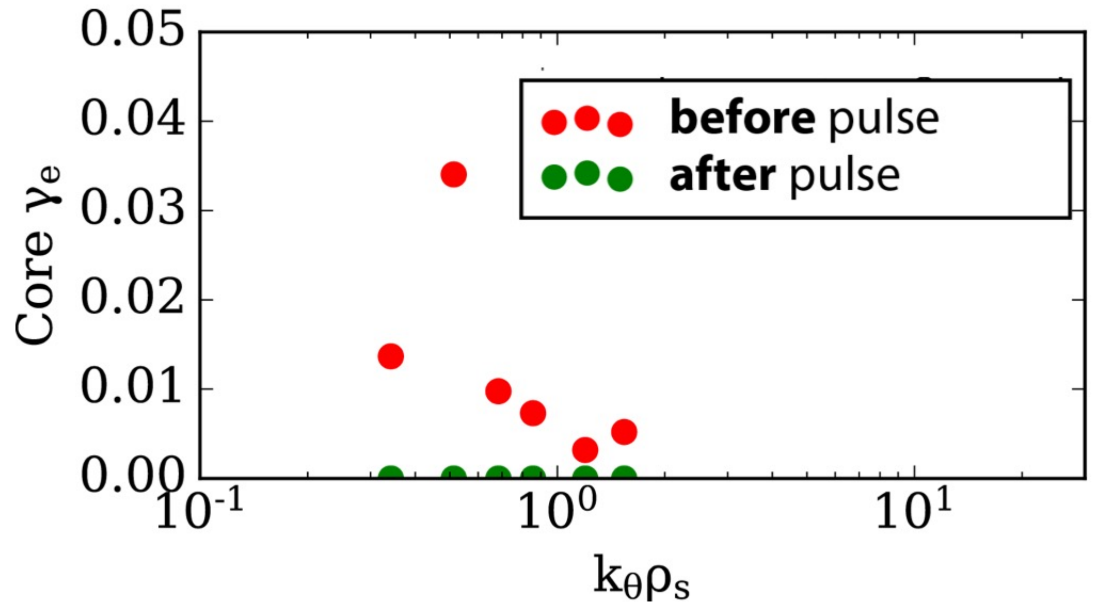
Reconciling "nonlocal observations" with local models required high-stiffness of TGLF-SAT1

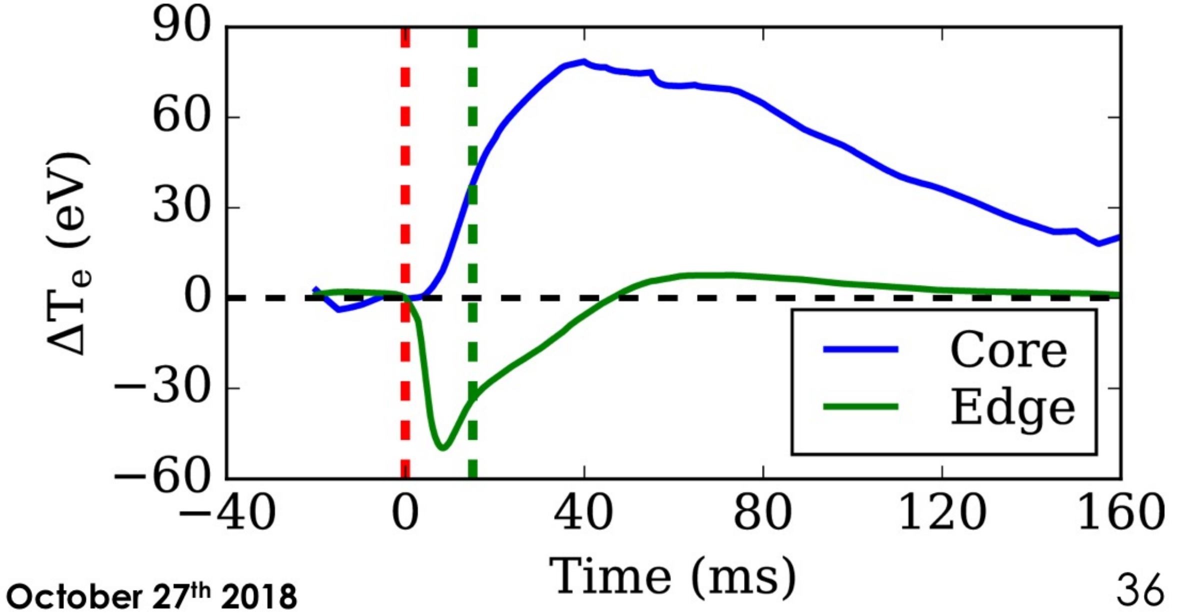
- Past work referred to these as **nonlocal effects**, as local plasma parameters seemed unchanged before T_e increases.
- **Modest change in density** leads to T_e increase.
- **Change in gradients** (& ν_{ie}, Z_{eff}) provides enough TEM stabilization.



Core growth rates (only electron direction)



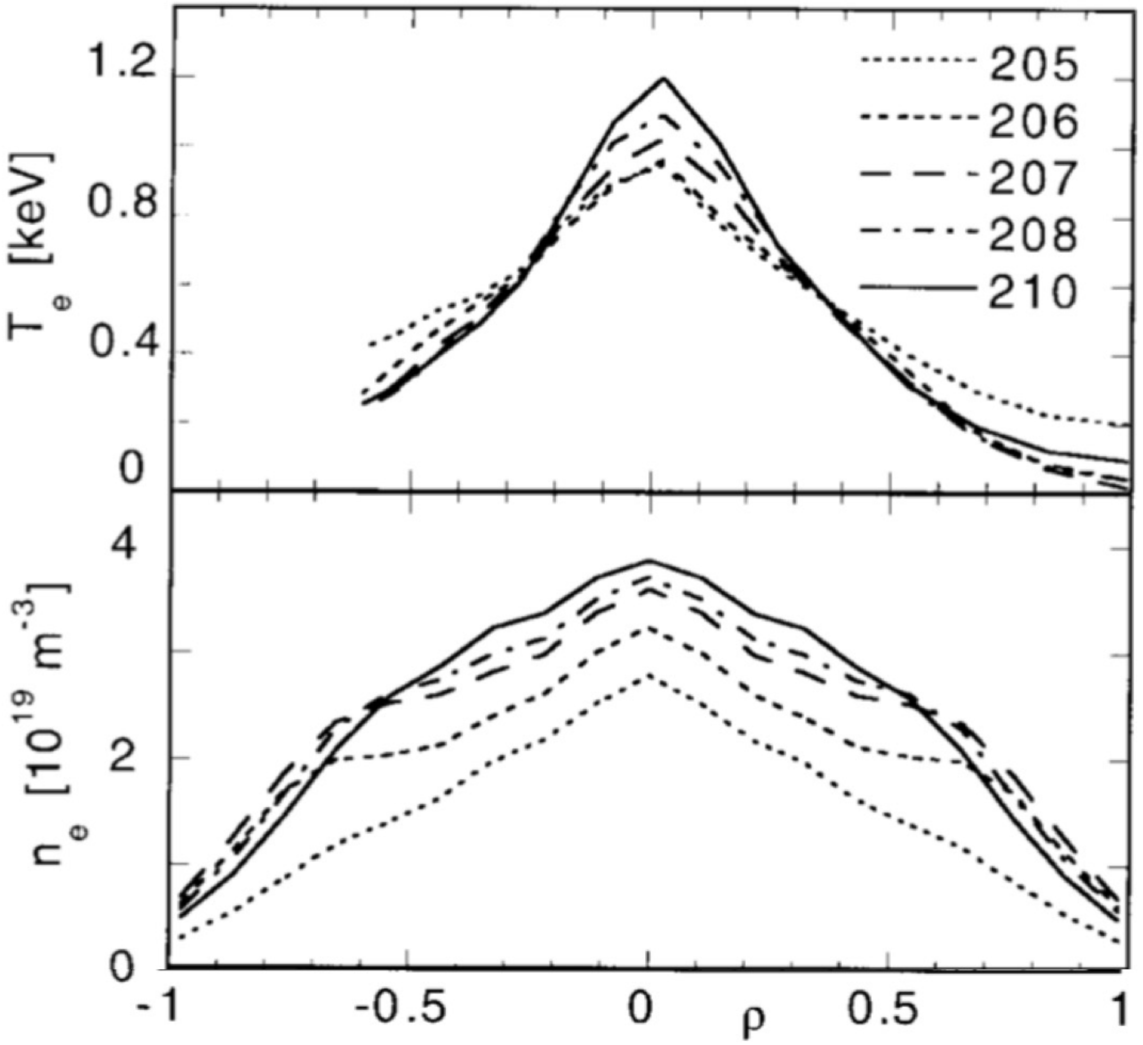
Core and edge temperatures



Density perturbation is needed to recover cold-pulse phenomenology, but widely observed experimentally

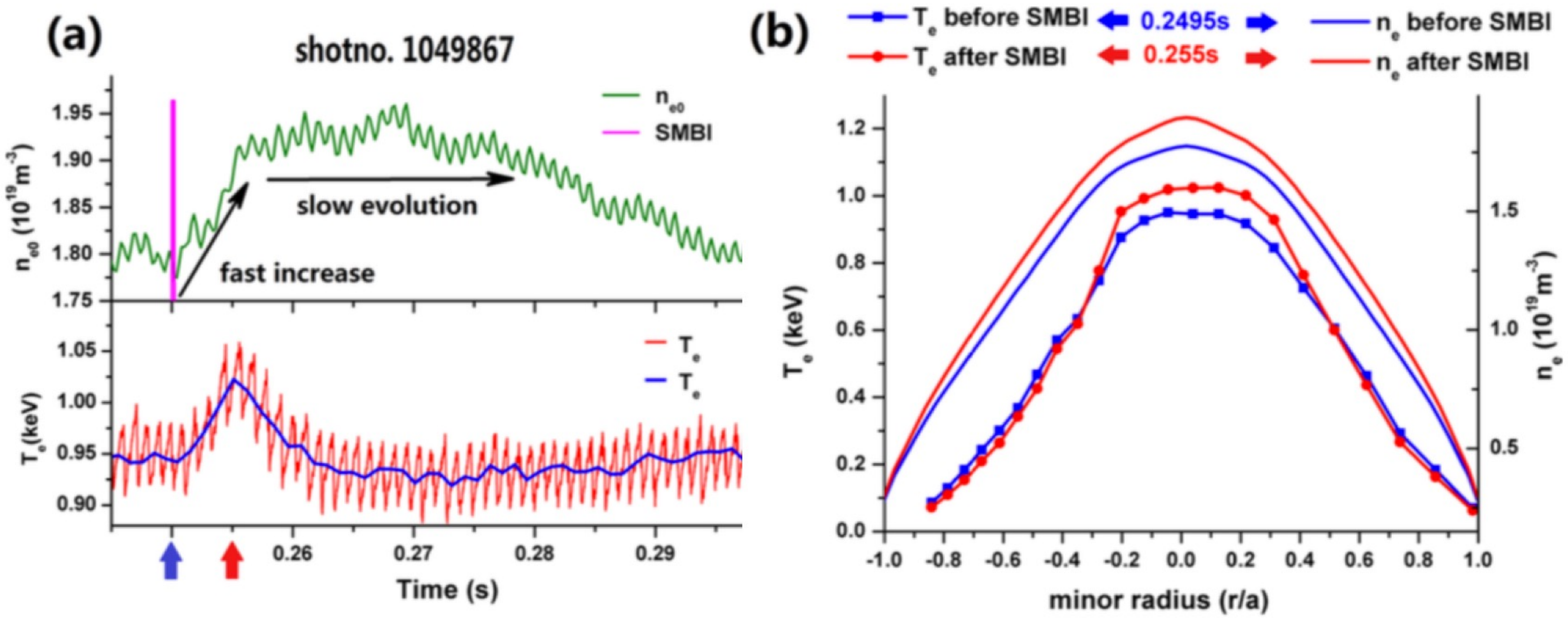
[Galli, NF '99]

RTP

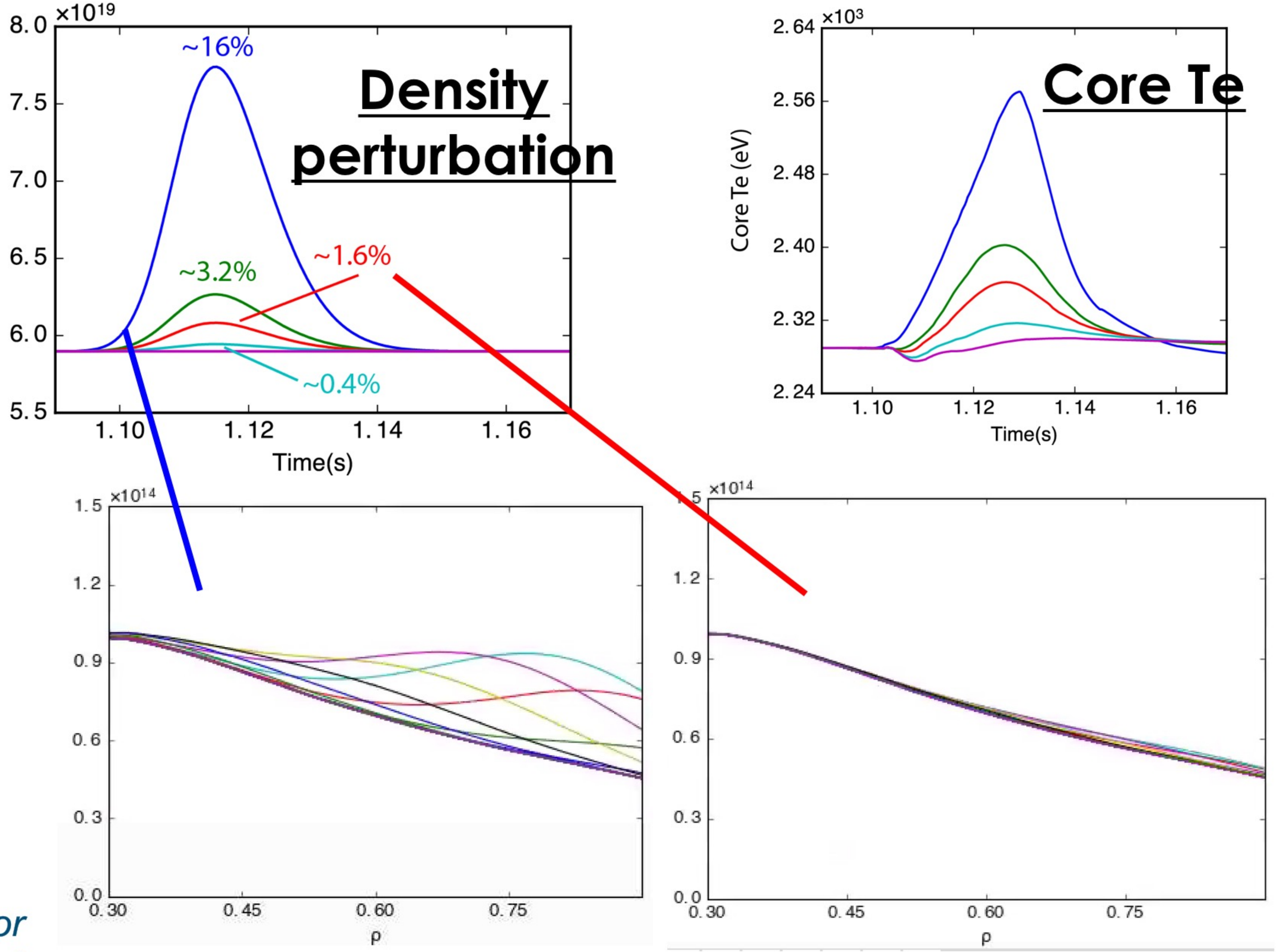


J-TEXT

[Shi, NF '18]

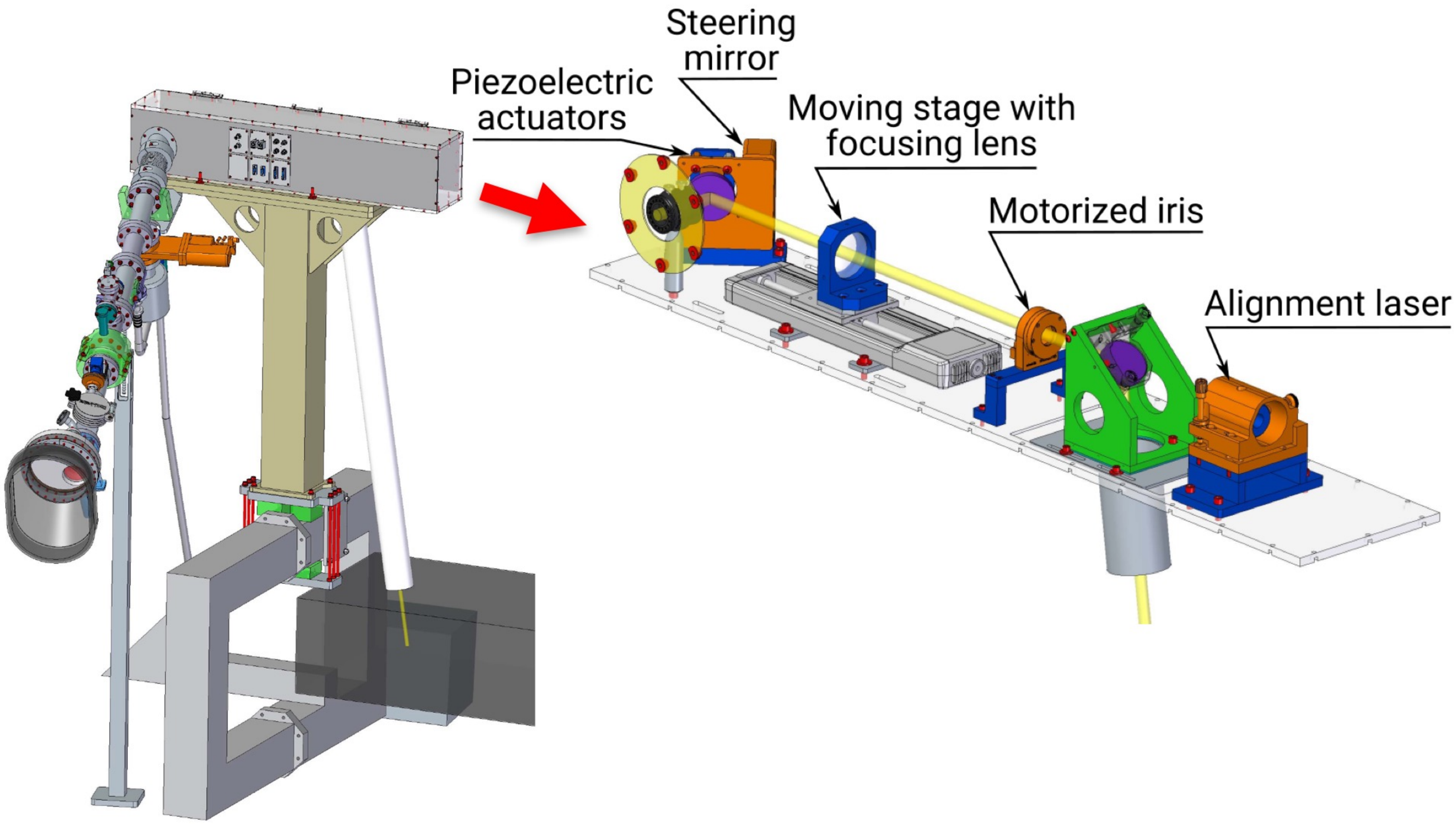


In C-Mod, density perturbation magnitude scan shows that temperature inversions are still recovered with small density pulses

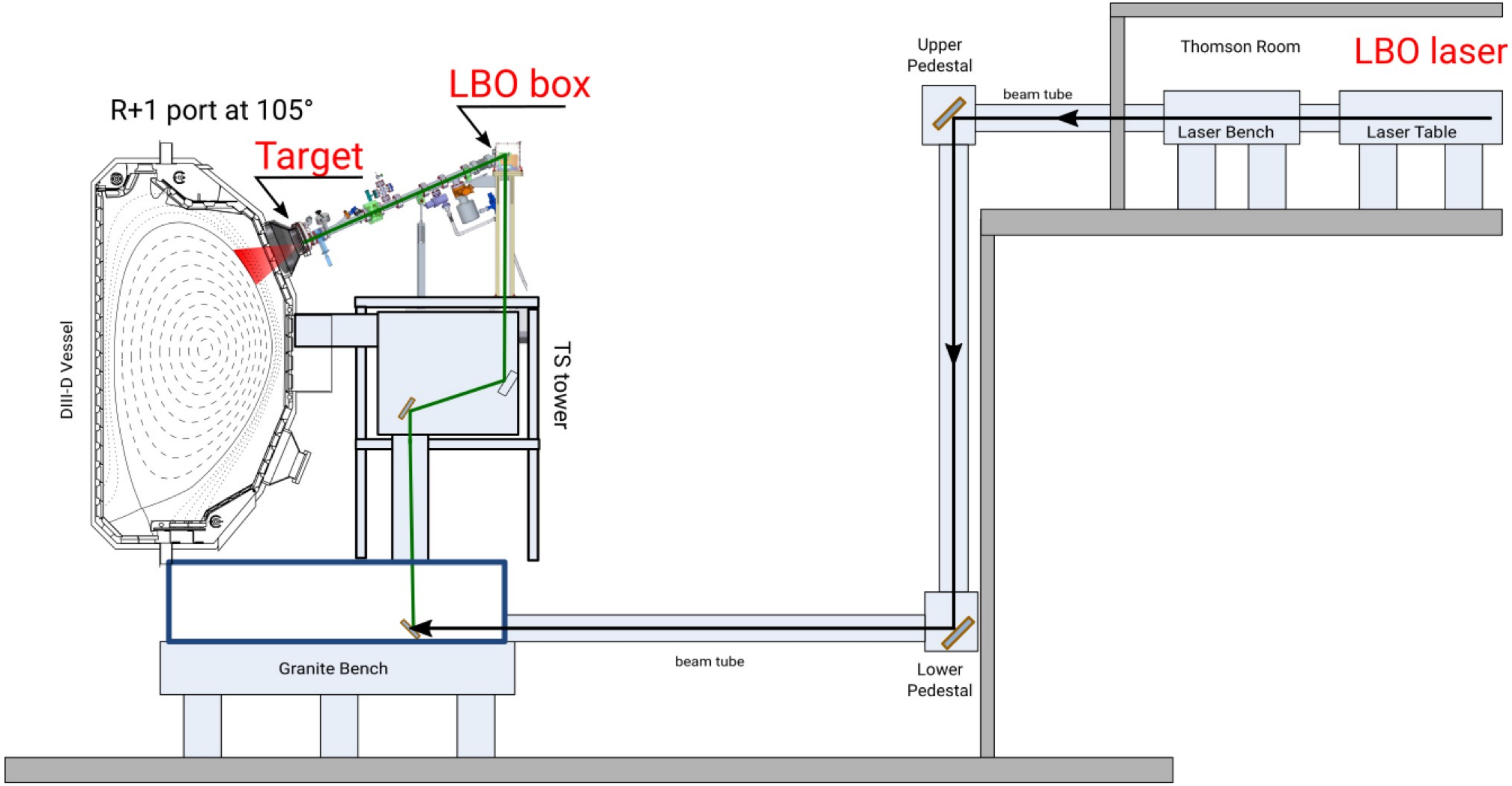


MIT Laser Blow Off (LBO) is providing capabilities for transport studies on DIII-D

- **MIT LBO commissioned in Feb. 2018 at DIII-D (T. Odstrcil & N.T. Howard)**
  - ❑ Injection of trace impurities into DIII-D core plasma for routine investigations in impurity transport and confinement.
  - ❑ Also, specialized cold pulse heat transport experiments.



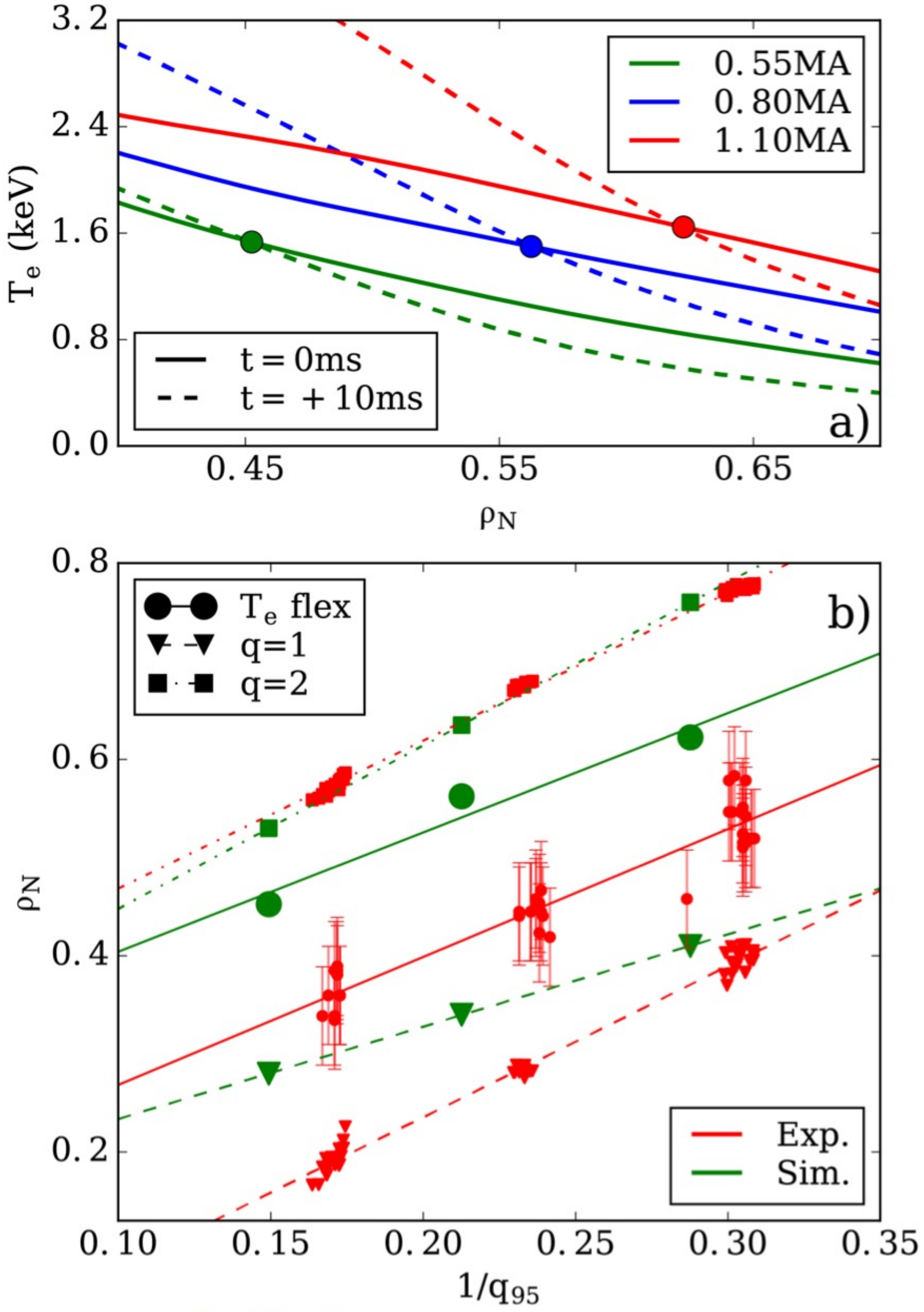
The DIII-D LBO System is Integrated with the DIII-D Thomson System and Attached to the 105R+1 Port

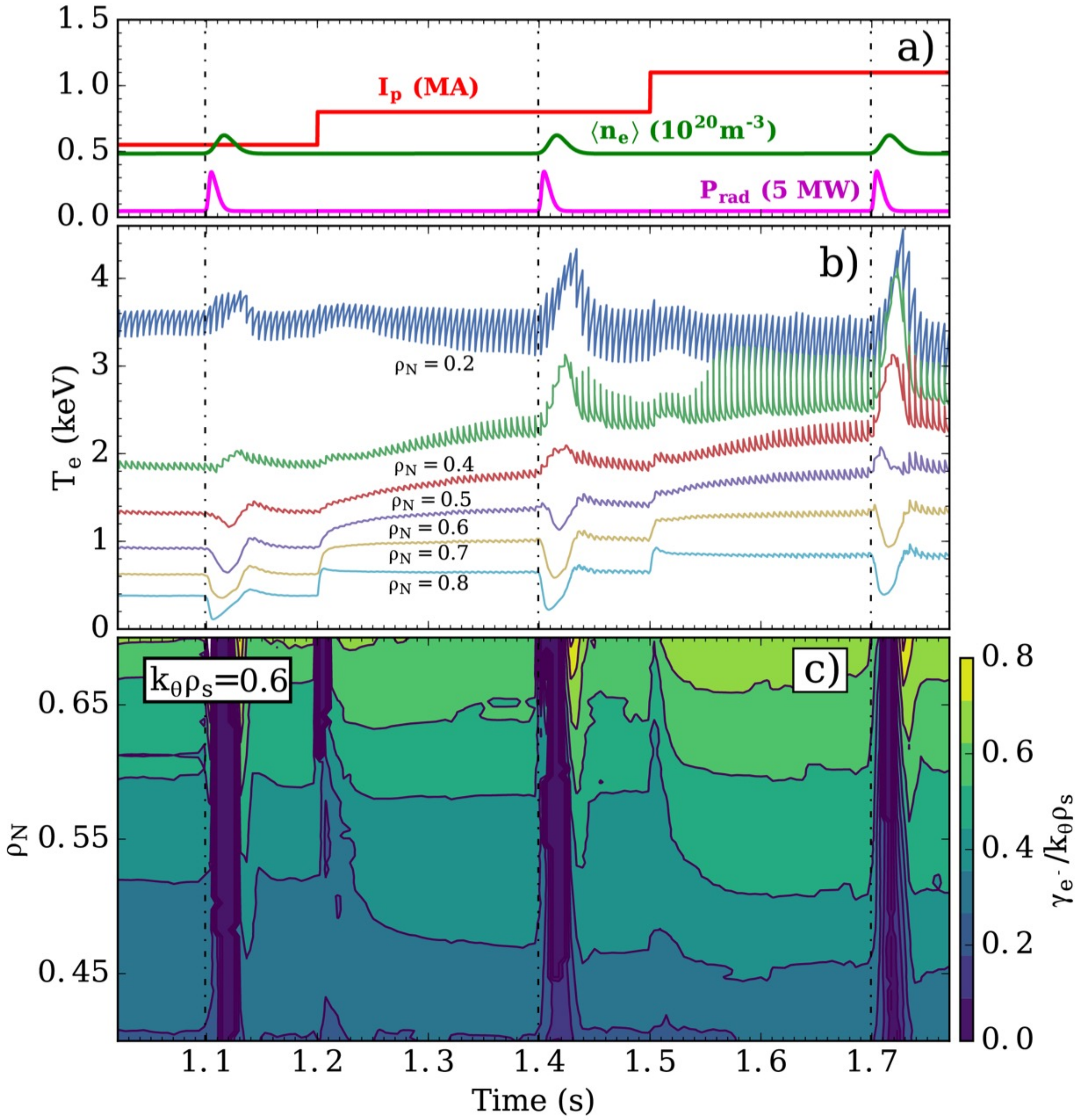


Back-up Slides

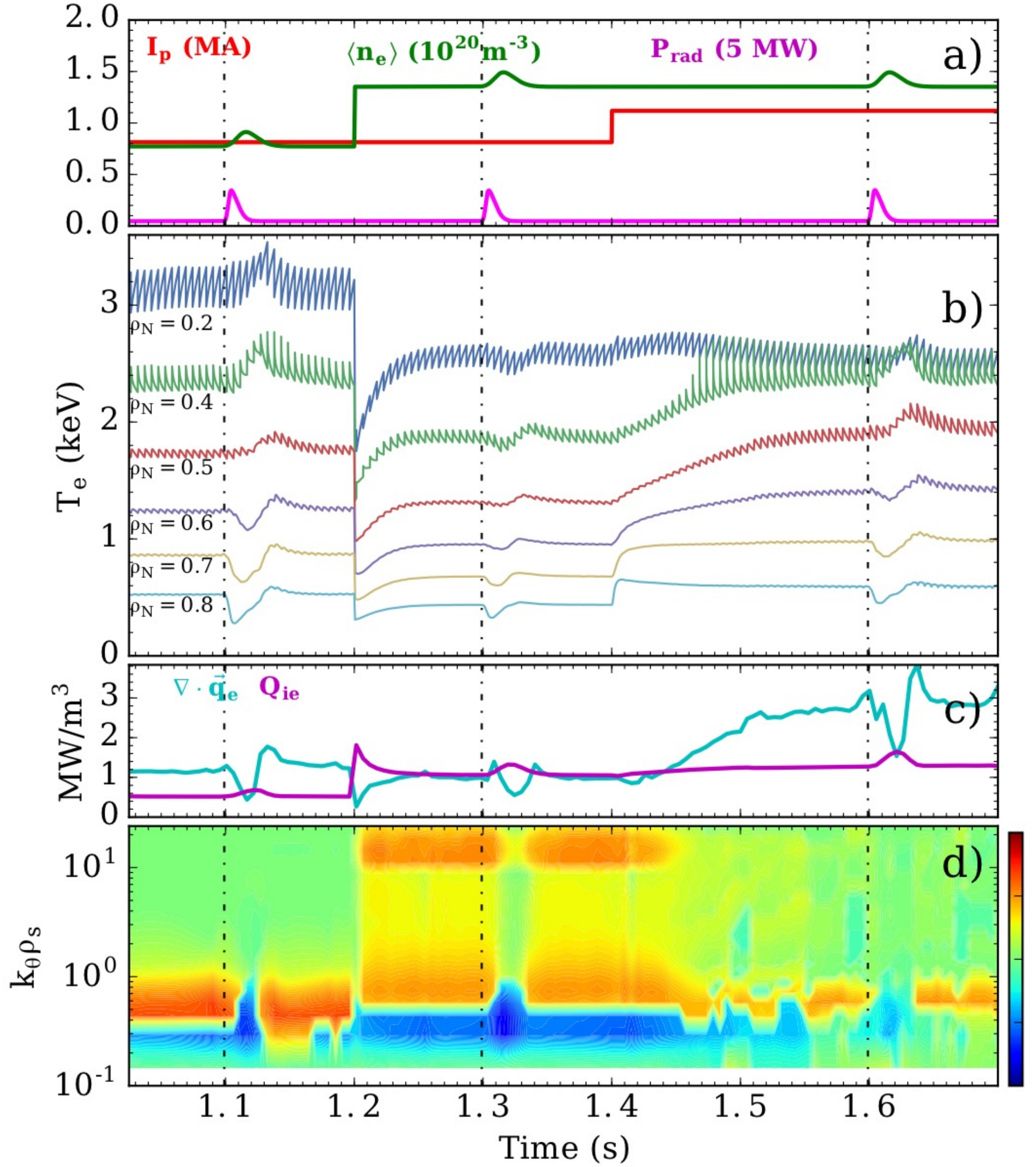
C-Mod Modeling (ext.)

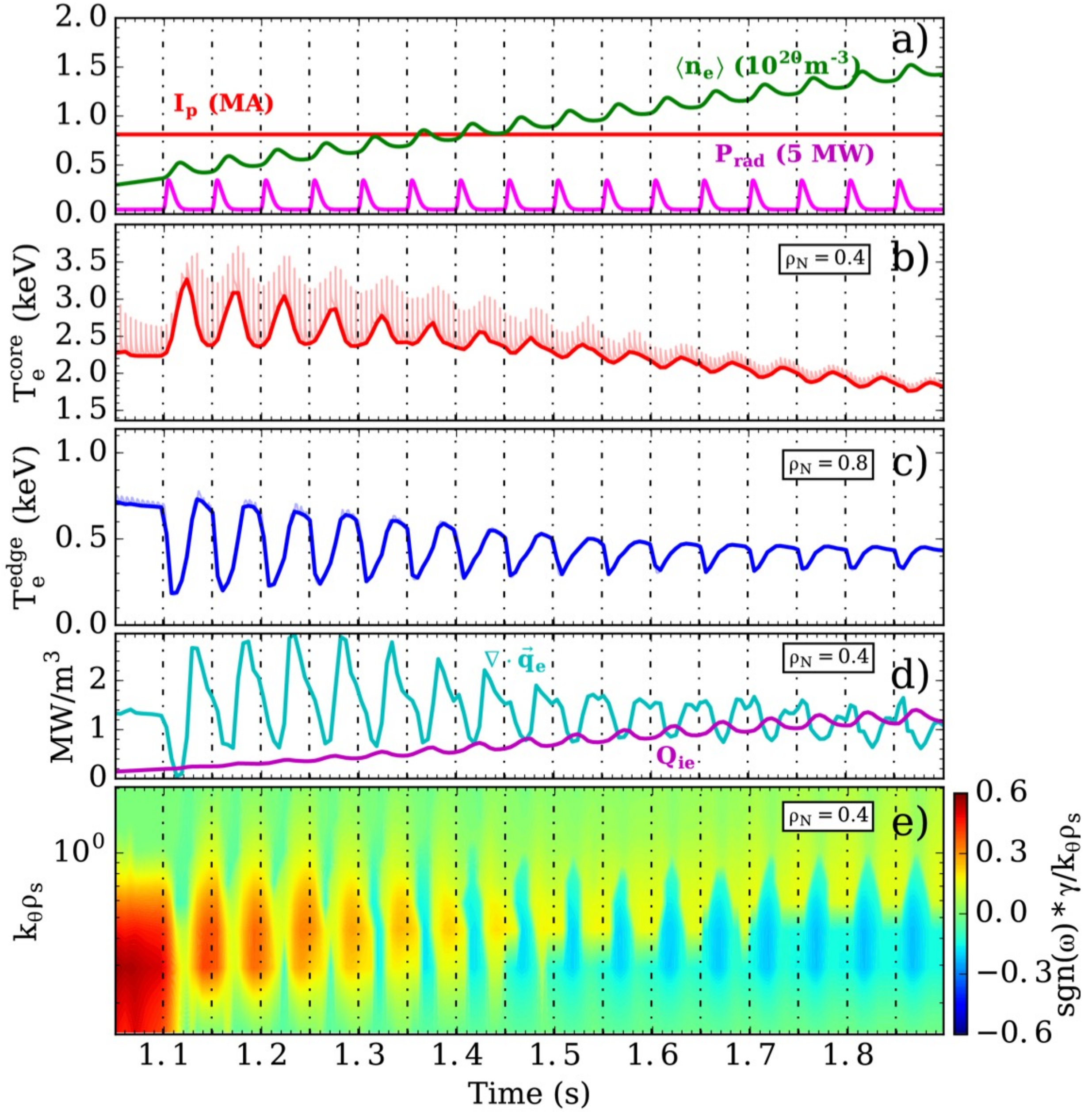
Simulation at fixed density with current steps shows that position of “temperature flex point” moves with rational surfaces, as observed experimentally



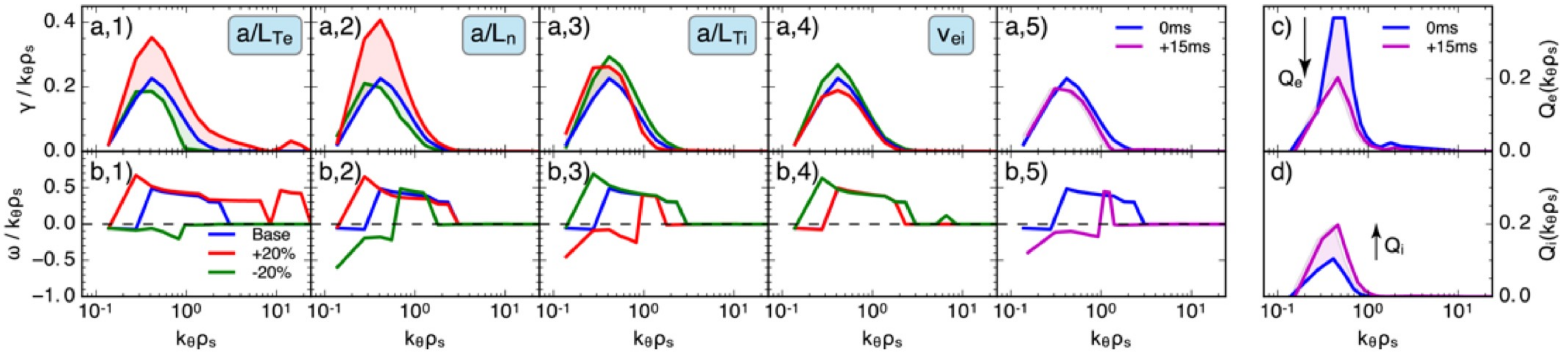


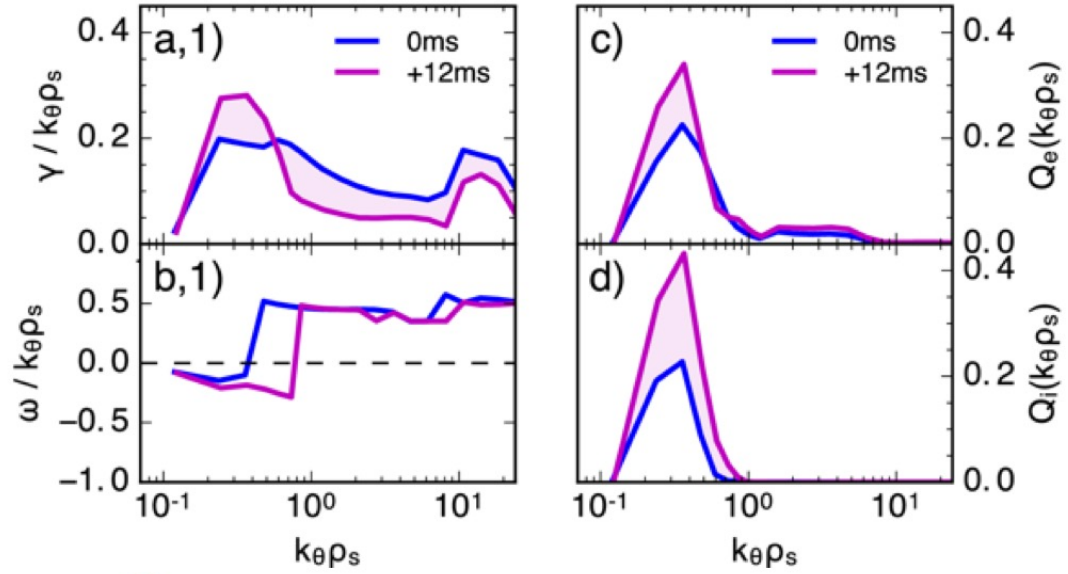
Simulations with density ramp and density steps show that experimental trend is well-captured and transition happens as ITG/TEM transition occurs

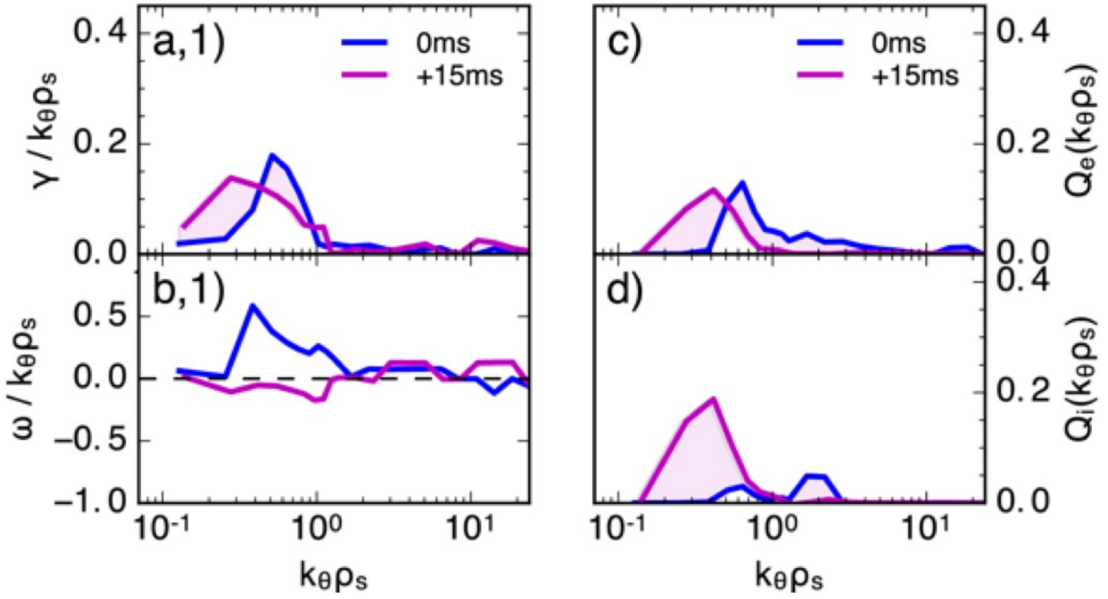




Linear stability analysis shows that temperature inversions occur when electron turbulent transport is more sensitive to TEM drives



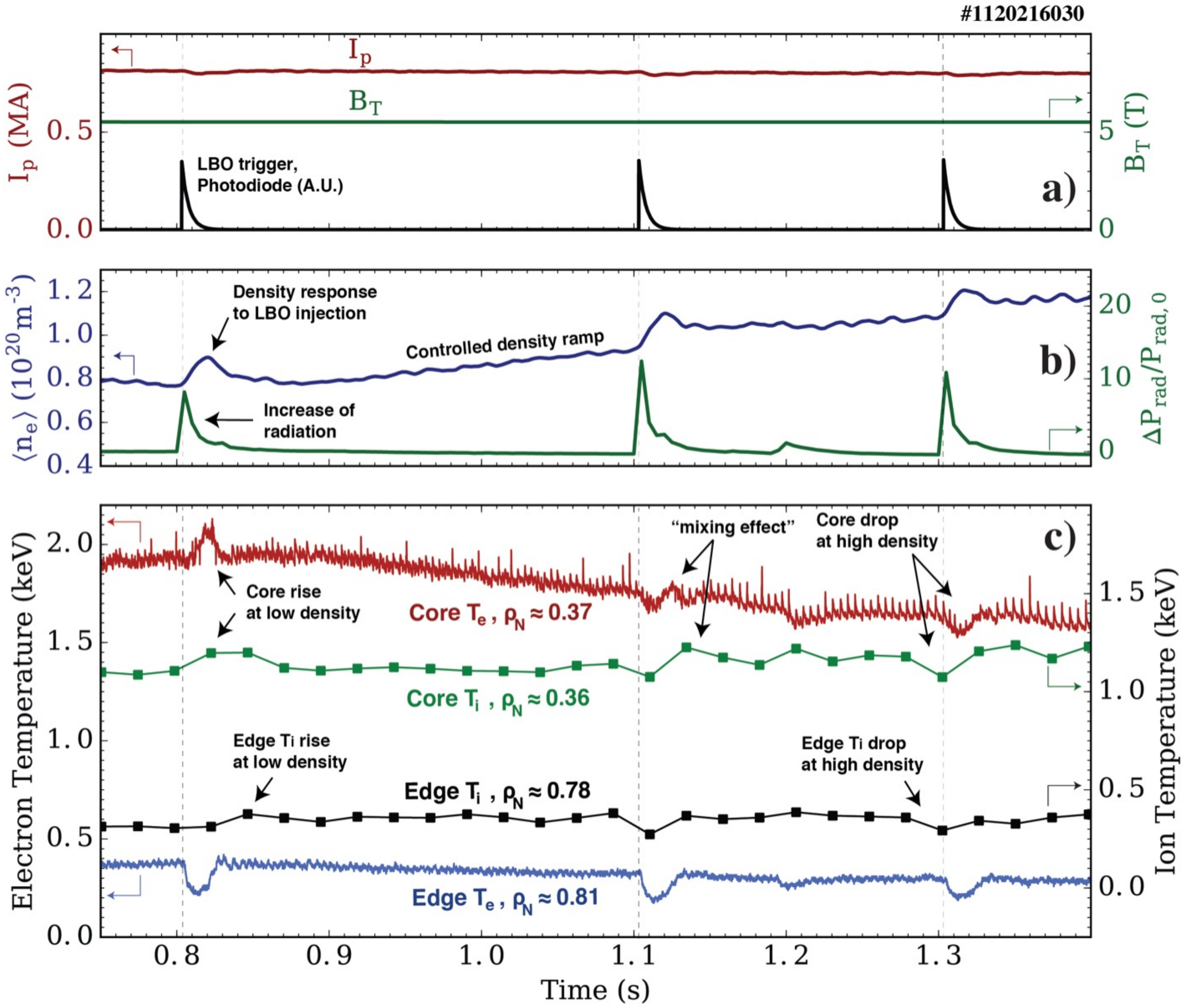




Back-up Slides

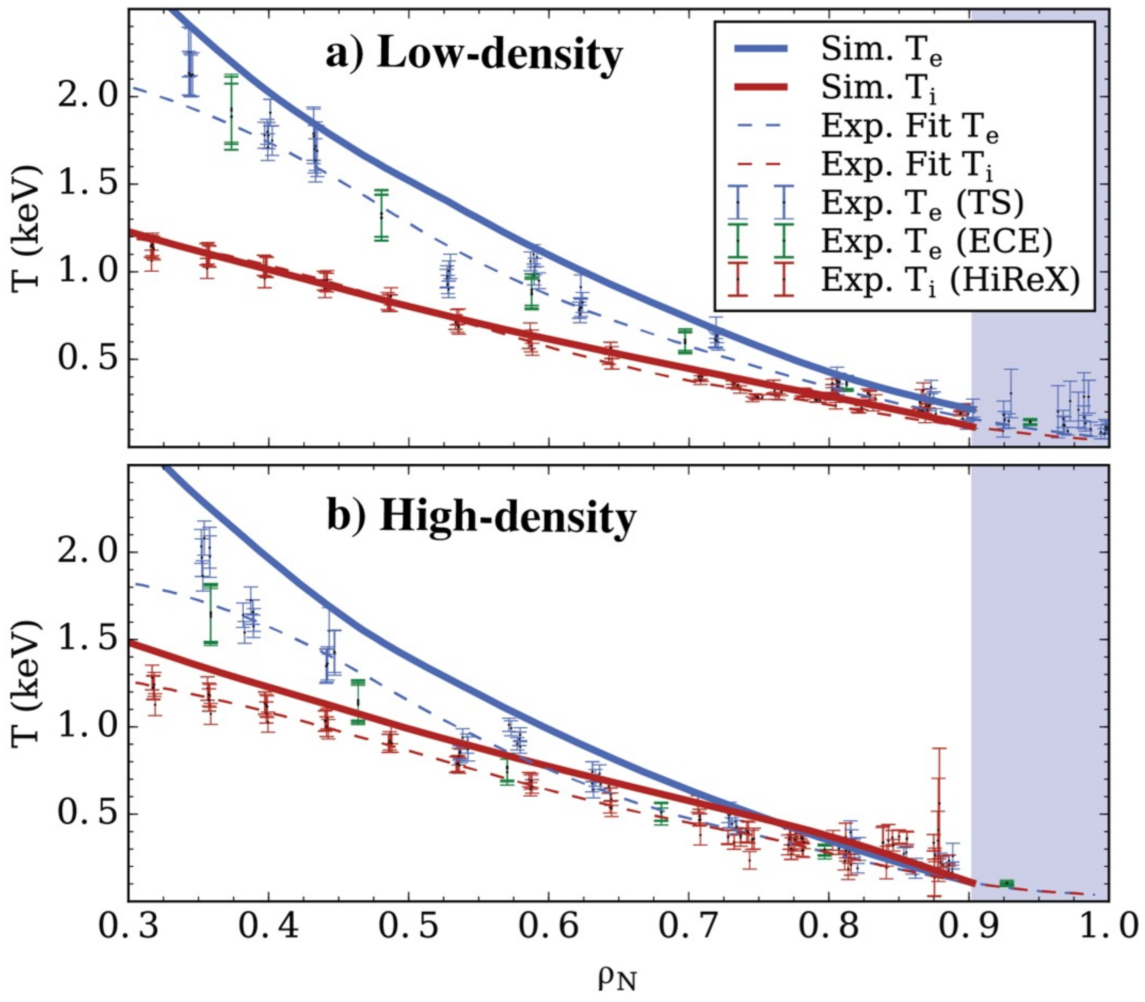
C-Mod Modeling (PRL)

Ohmic C-Mod discharge with density ramp that exhibits LOC/SOC transition is used for cold-pulse studies

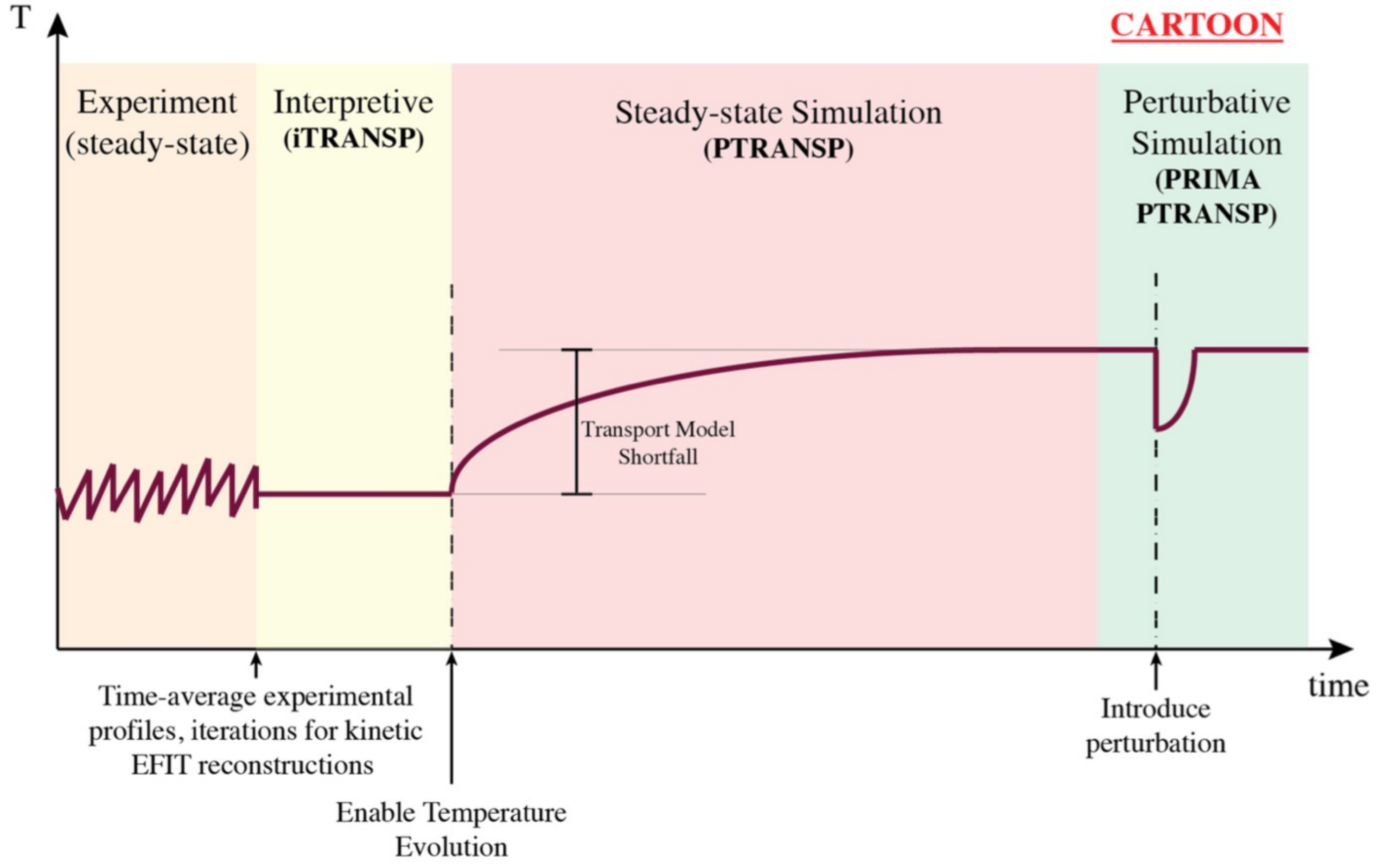


Ion and electron temperatures are evolved until reaching steady-state in the simulation

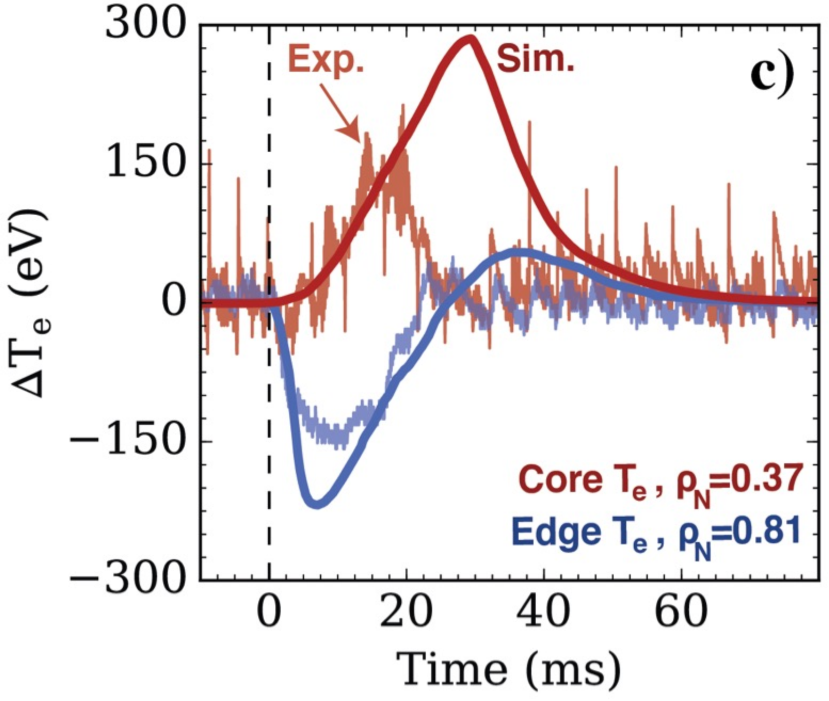
- Before introducing perturbation in P_{rad} and n_e, steady-state must be reached in the simulation.

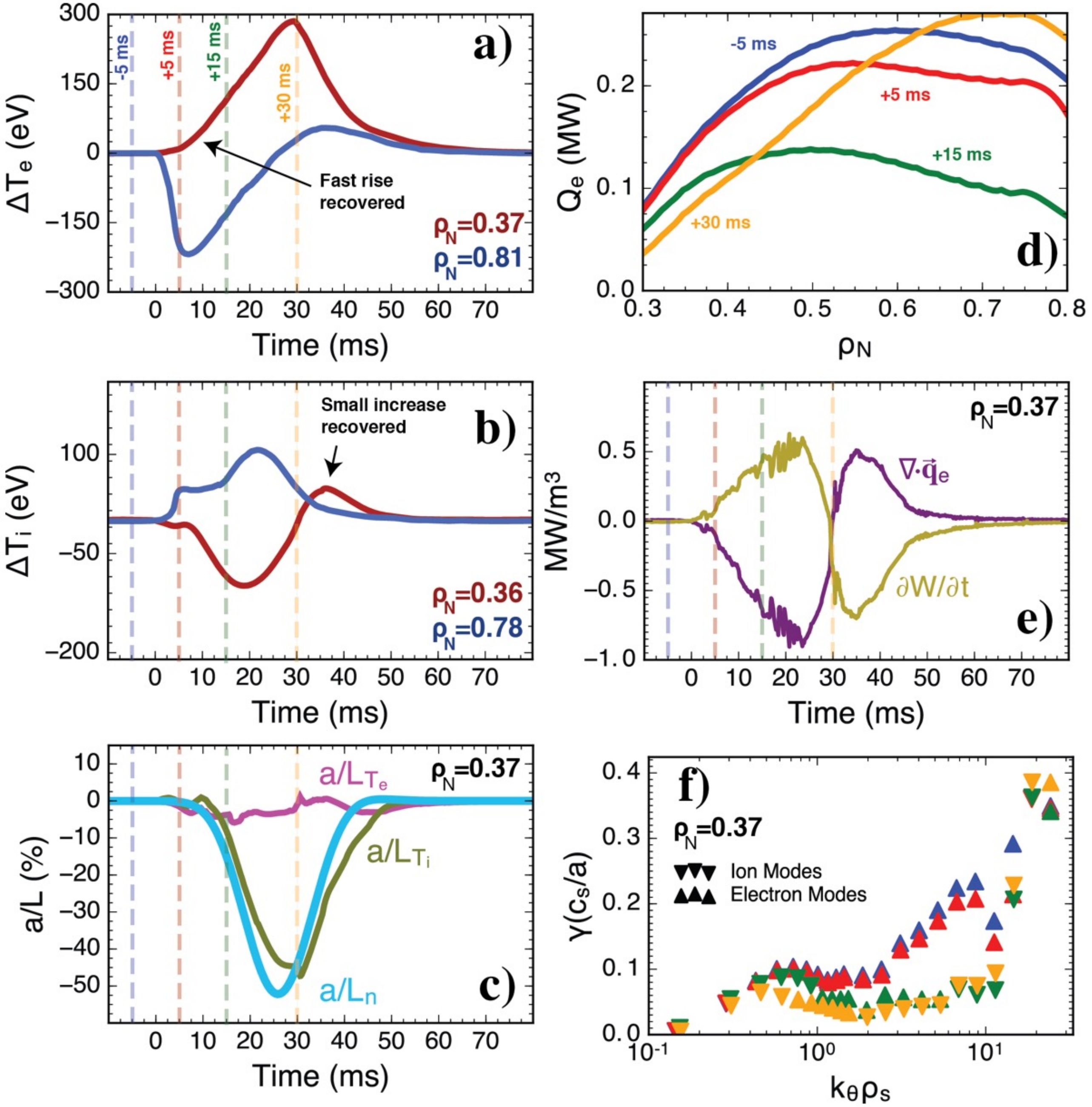


- Boundary conditions for T_e and T_i are chosen at $\rho_N = 0.9$.
- Predicted profiles close to experimental values (within 2σ).
- Turbulent and neoclassical transport as predicted (not tweaked).

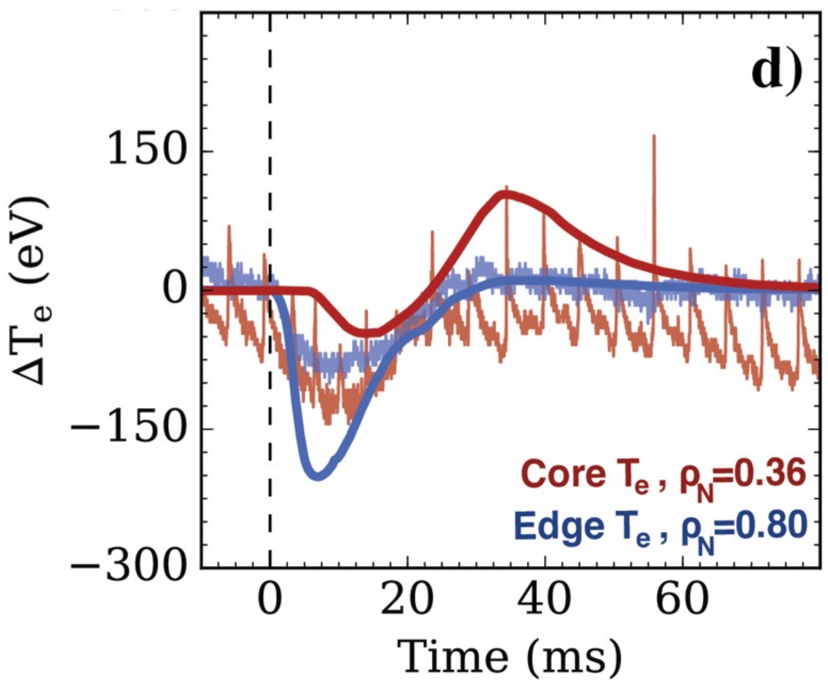


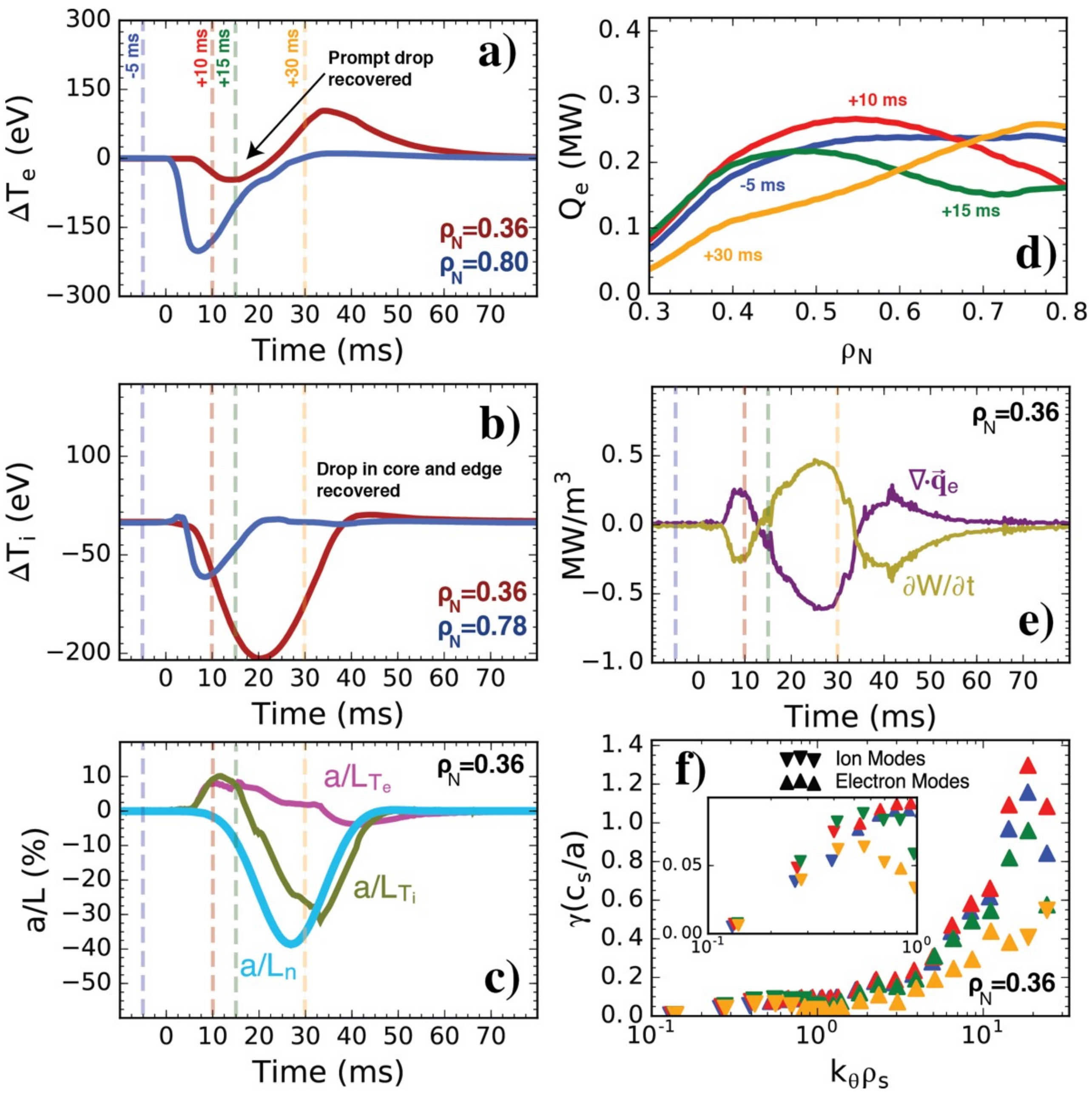
Core T_e inversions following edge cold-pulses appeared spontaneously in the TRANSP simulations with TGLF-SAT1





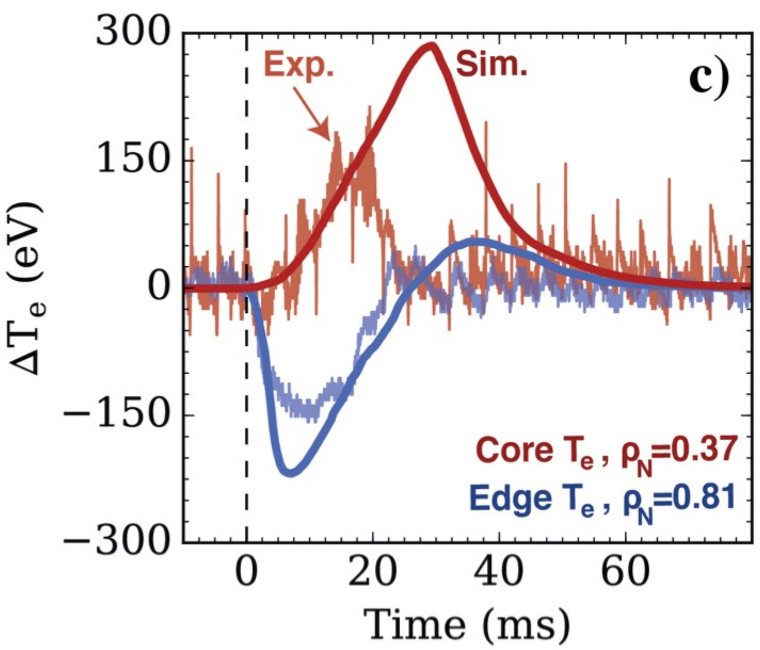
At high density, the prompt core T_e increase disappears and a “mixing effect” becomes evident

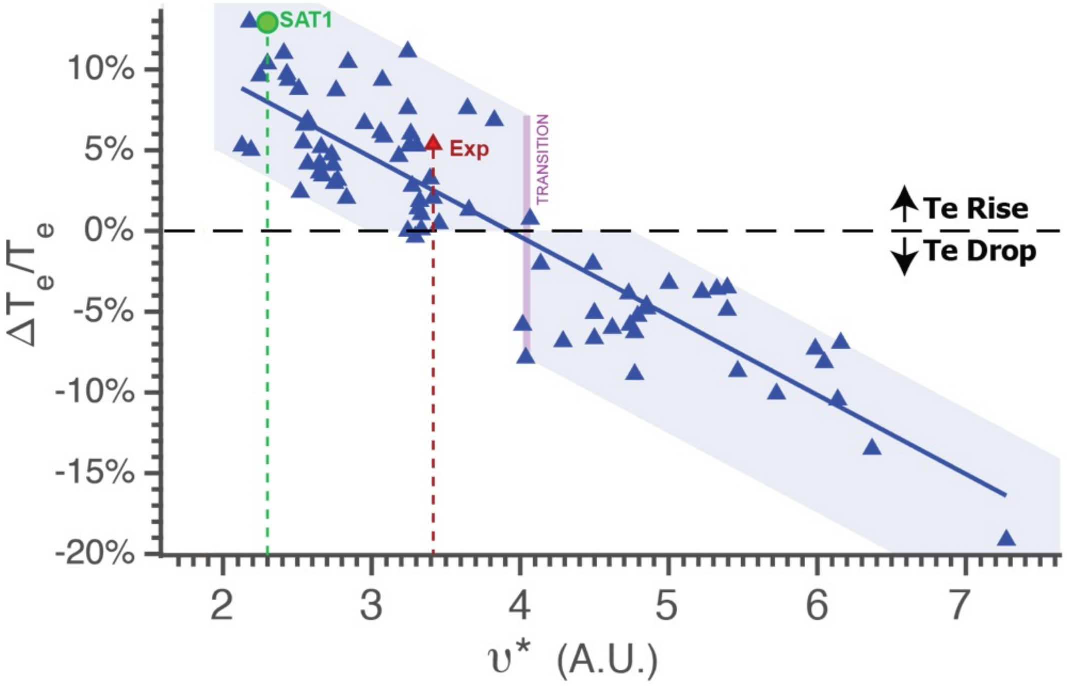


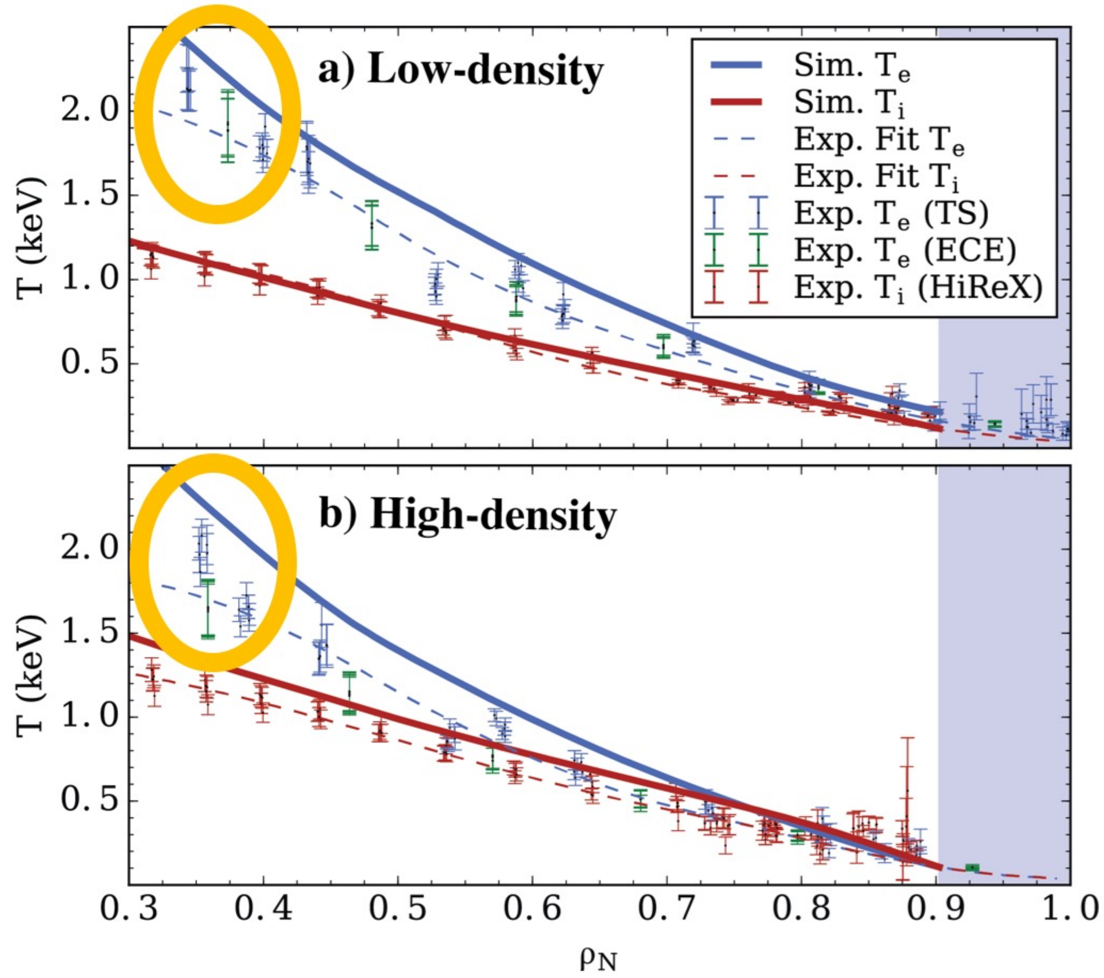


Differences in behavior can be explained by overprediction of steady-state temperature

- At low density, core temperature increase is higher than experimental value.

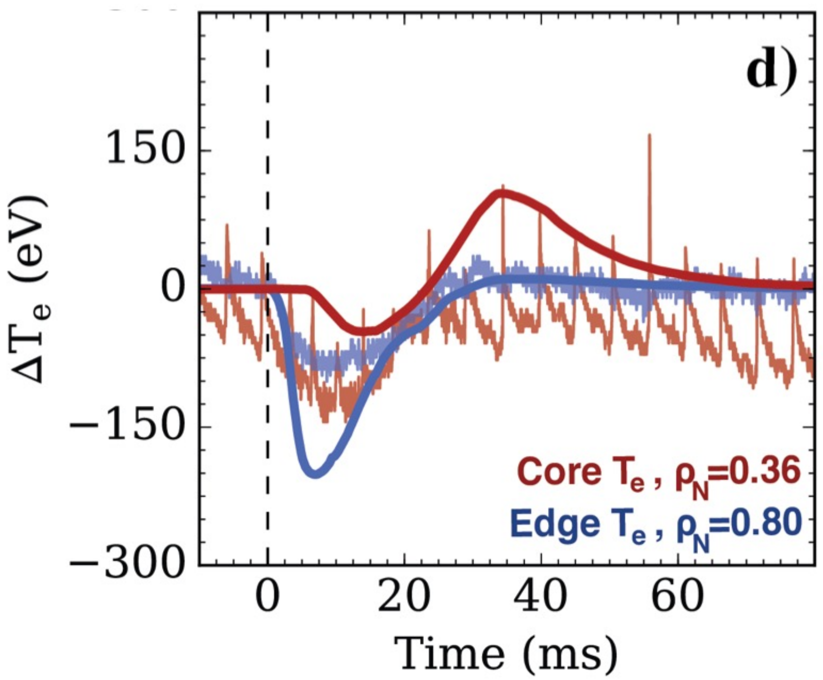


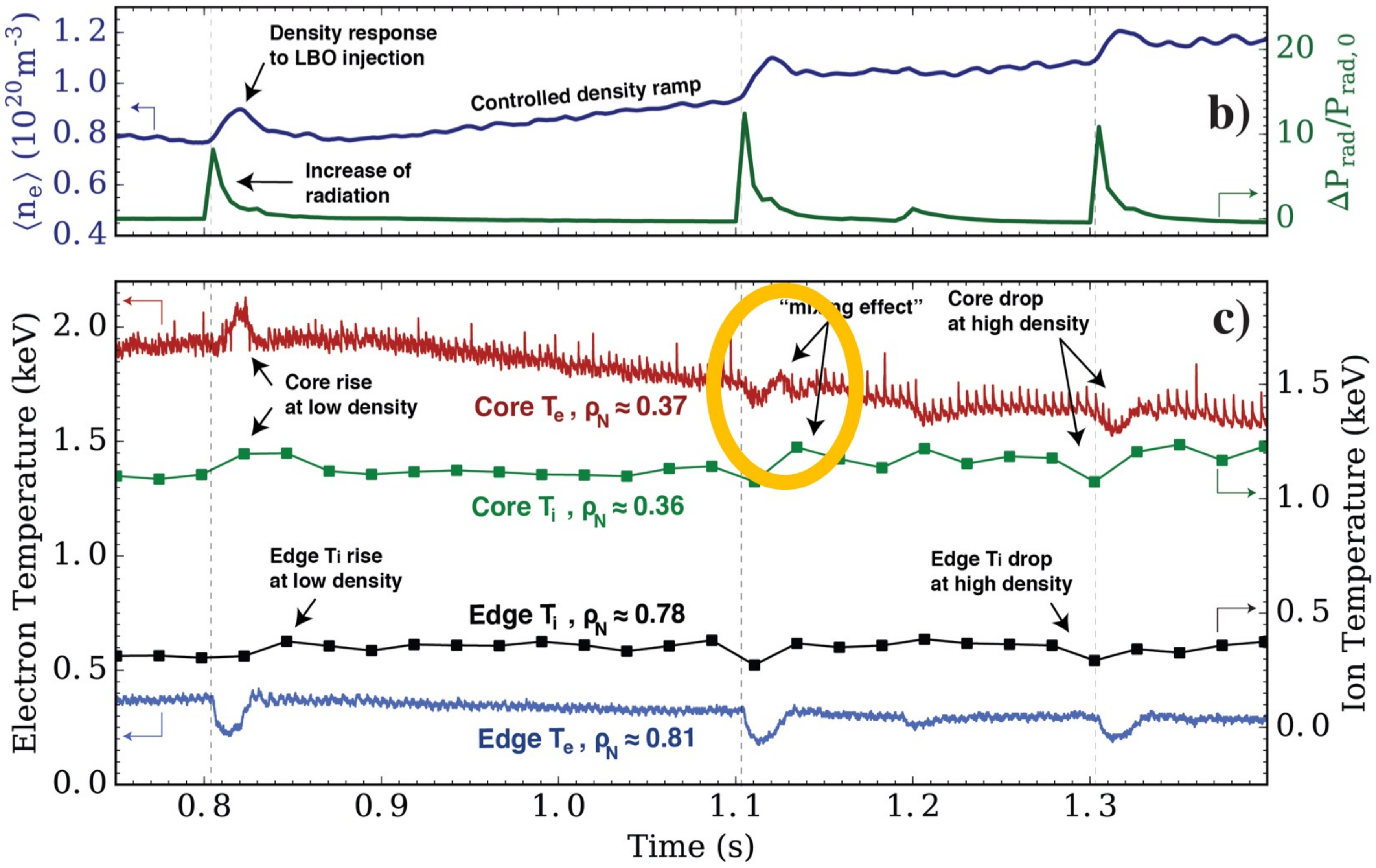




Differences in behavior can be explained by overprediction of steady-state temperature

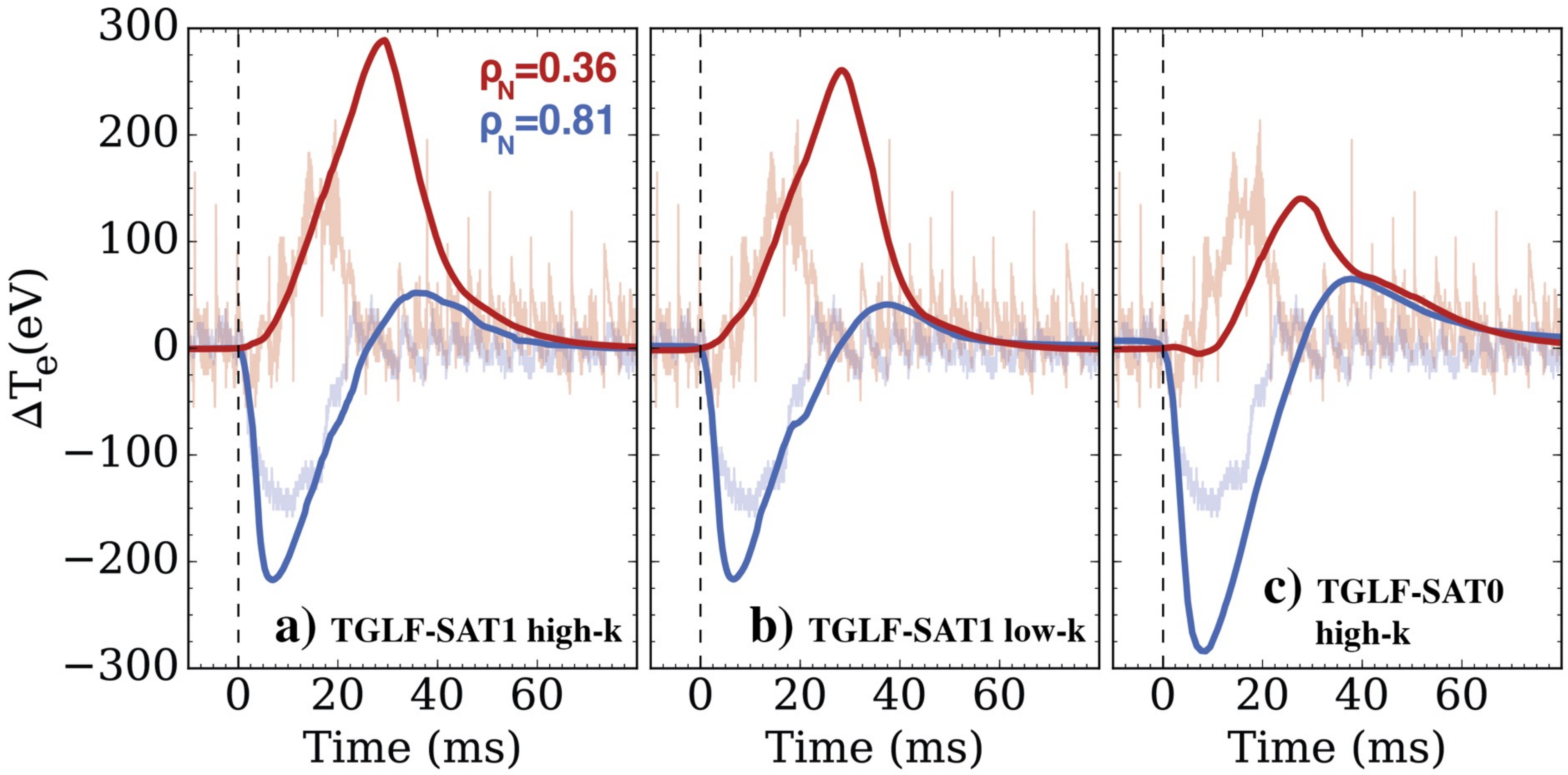
- At high density, core temperature drops and then increases.



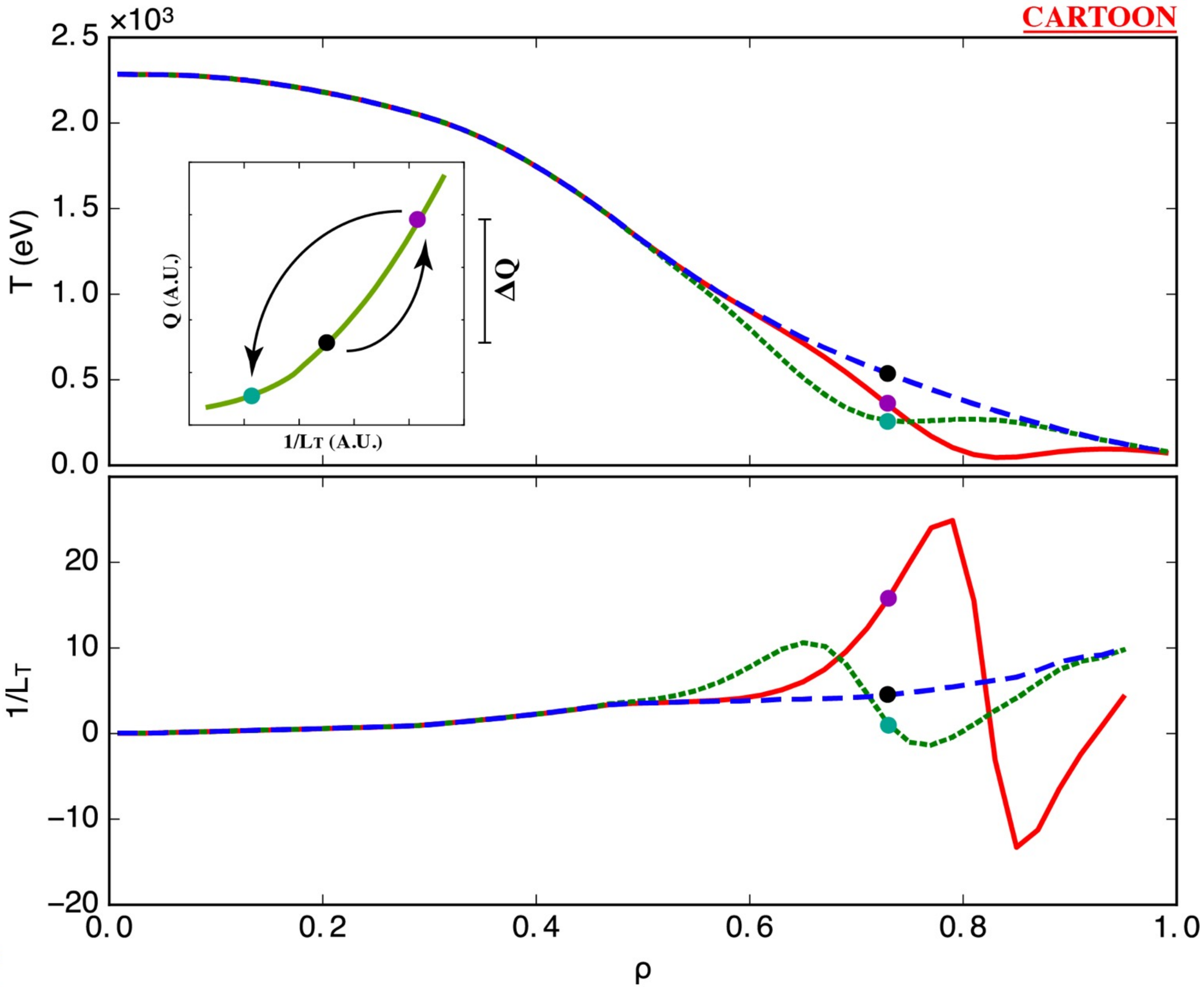


Full phenomenology is only recovered by new saturation rule TGLF-SAT1

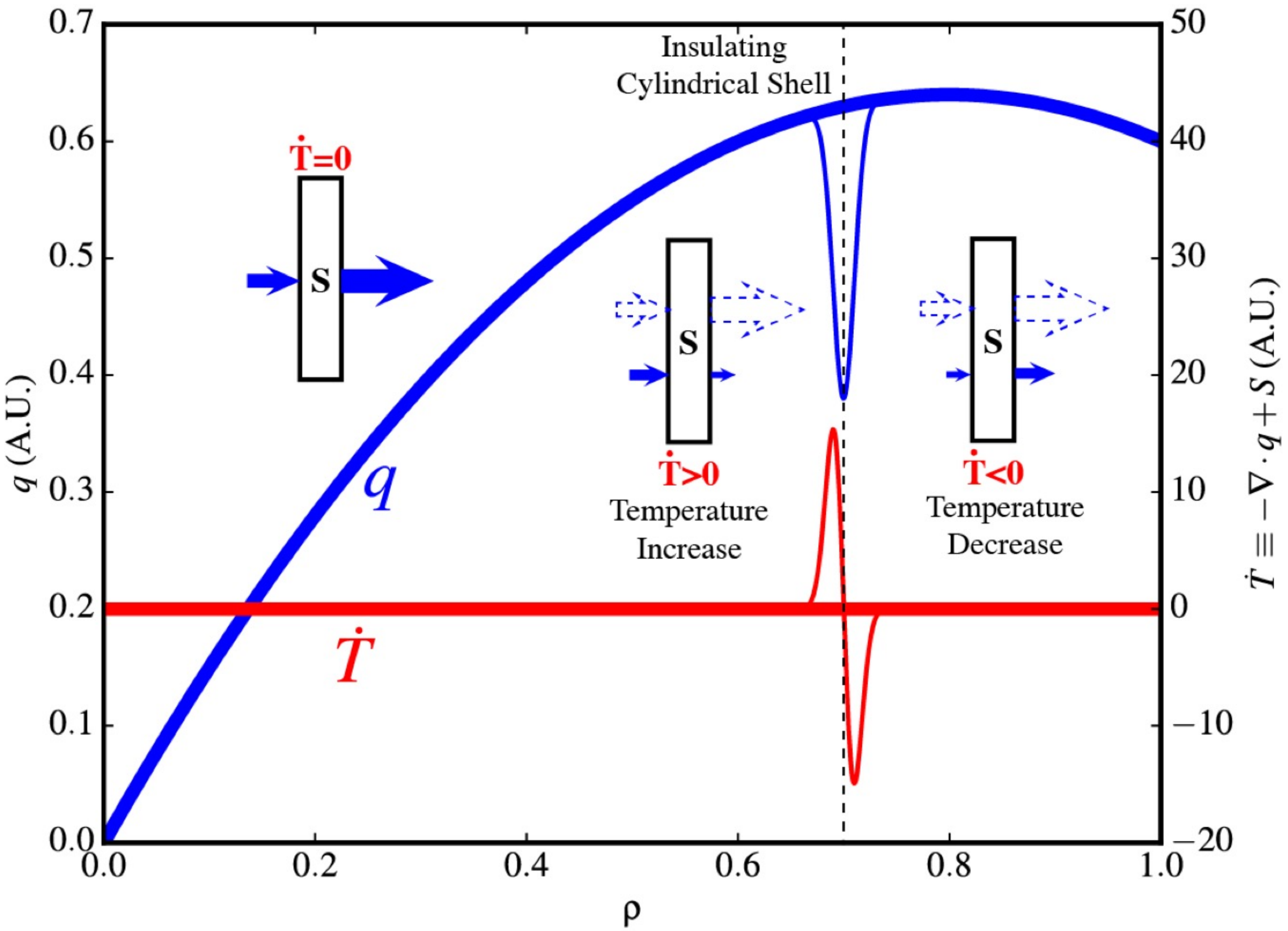
- TGLF-SAT1 with only low-k modes worked ➔ ETG "multi-scale" effects unimportant.
- TGLF-SAT0 could not reproduce the timing and inconsistent with υ^* scaling.
- SAT1 v.s. SAT0:
  - Nonlinear upshift of ∇T_{crit}
  - Higher χ^{inc}
  - Amplification of TEM



The propagating front of a cold-pulse is a region of higher gradient



A localized drop in heat flux leads to an increase in temperature inner in the core

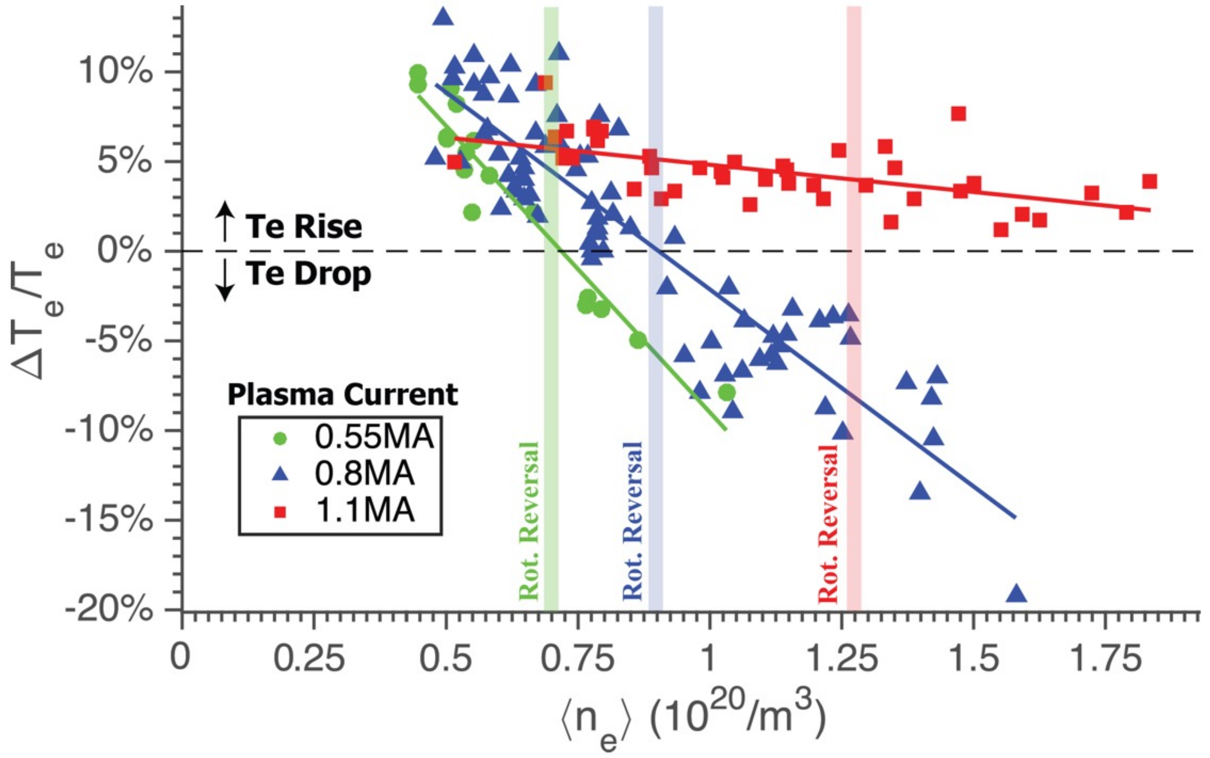


Back-up Slides

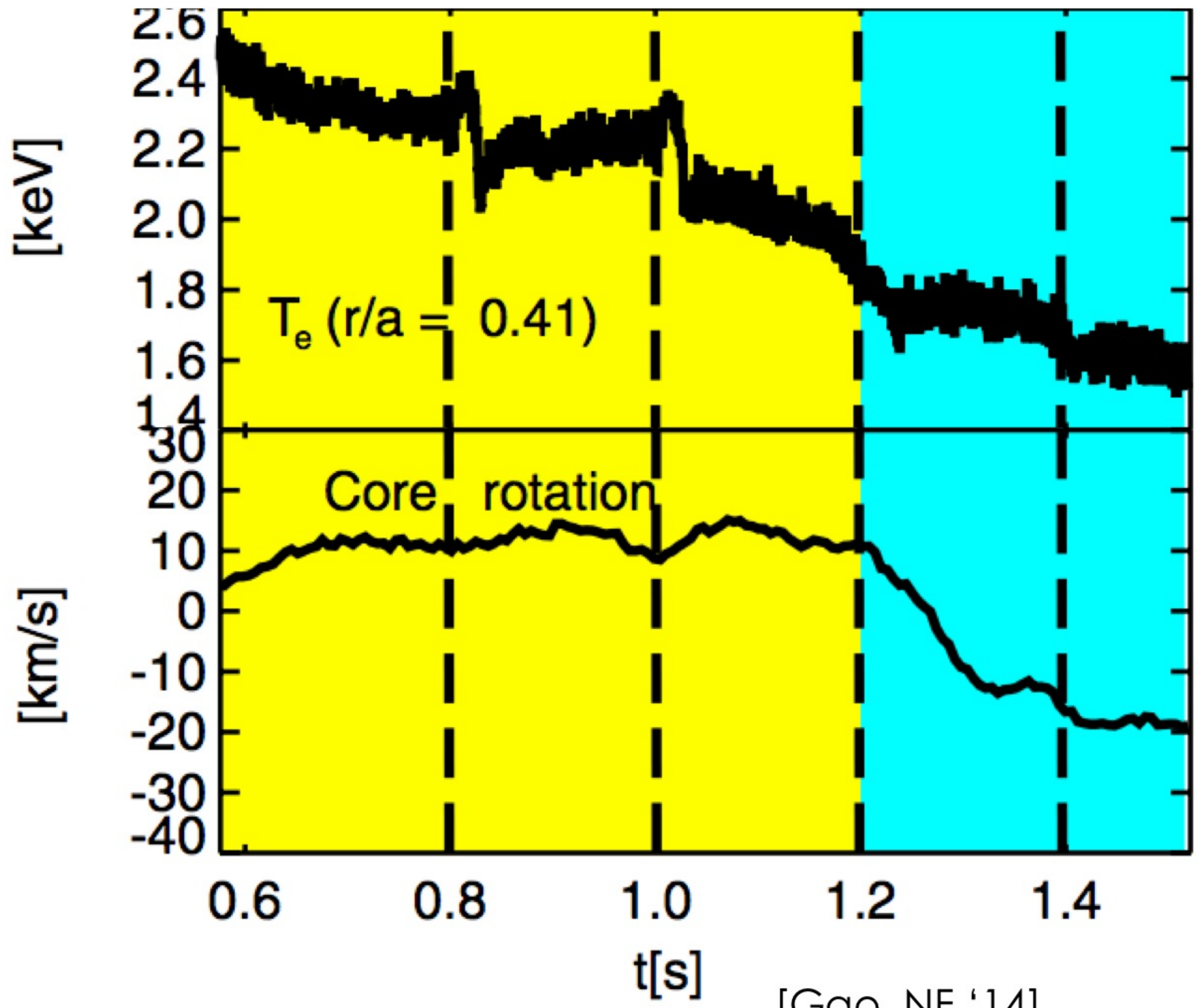
Cold-Pulse experiments (NF)

Recent work shows that correlation between these effects and intrinsic rotation reversals is not universal

- Transition density ≈ intrinsic rotation reversal.
- Relationship not found at high current.
- "Temperature inversions" decrease with increasing density (~ linearly), then vanish.



[Rodriguez-Fernandez, NF '17]

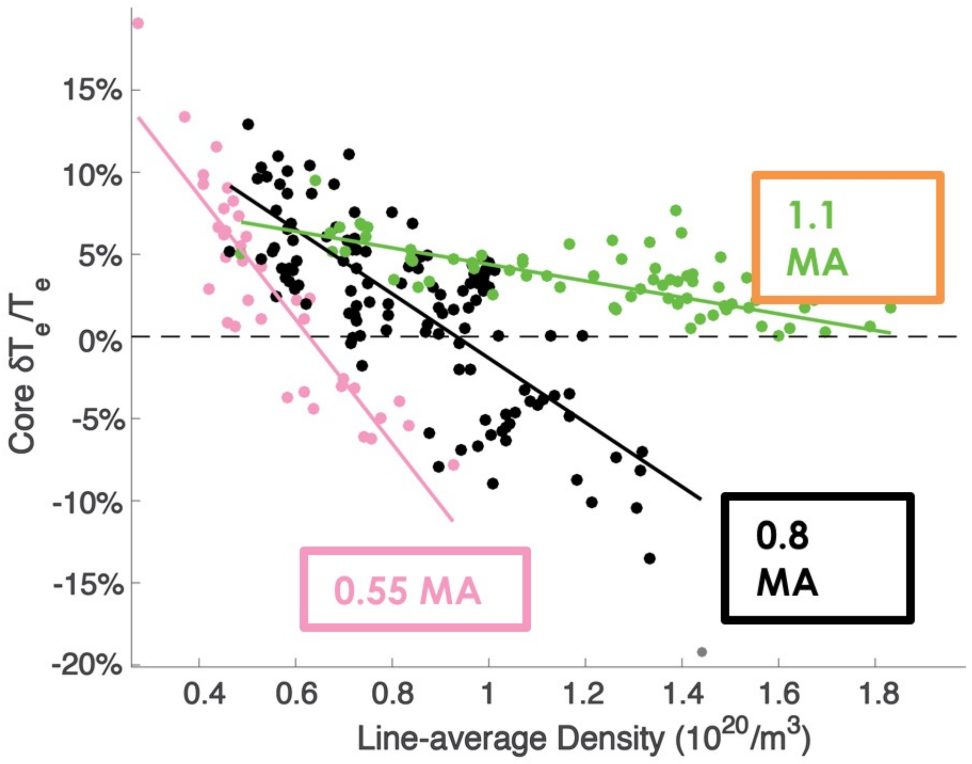


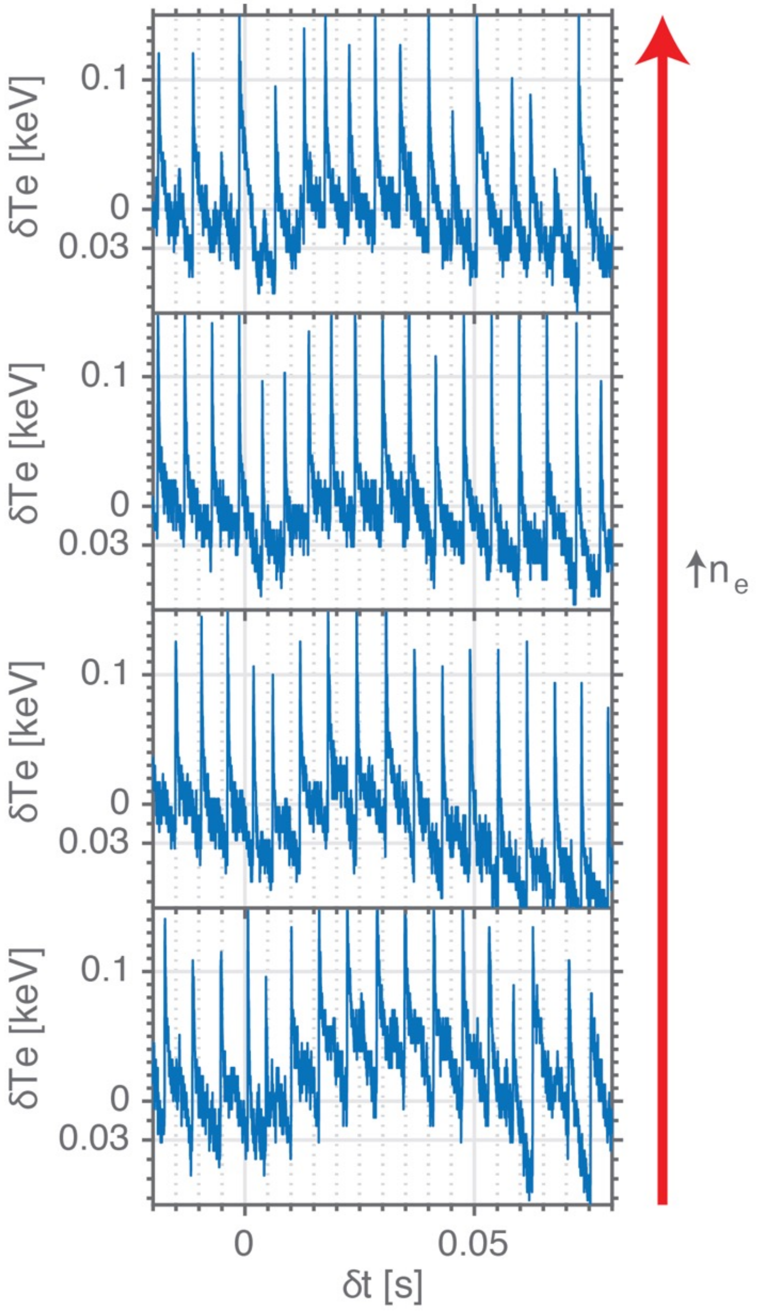
[Gao, NF '14]

MIT PSFC Alcator C-Mod

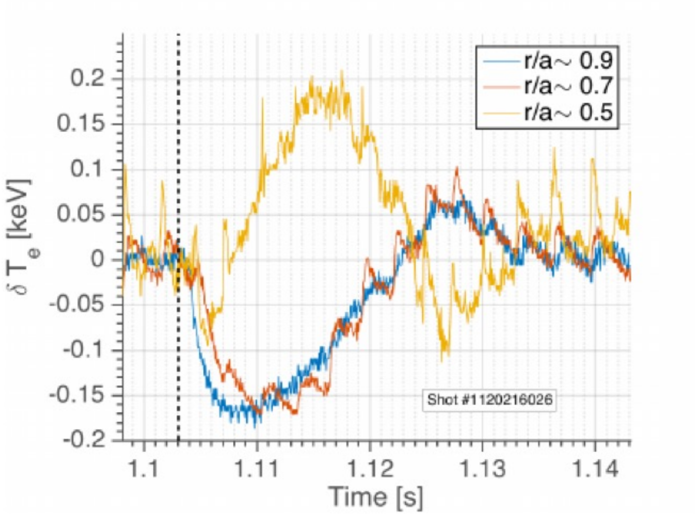
Shot-by-shot analysis show that transition to standard response is not abrupt

- In contrast to past work, transition from "non-local" to standard transport is smooth
- Core $\pm|\Delta T_e|$ depends strongly on I_p and P_{RF}
- At high I_p, inversions persist at HIGH $\langle n_e \rangle_l$

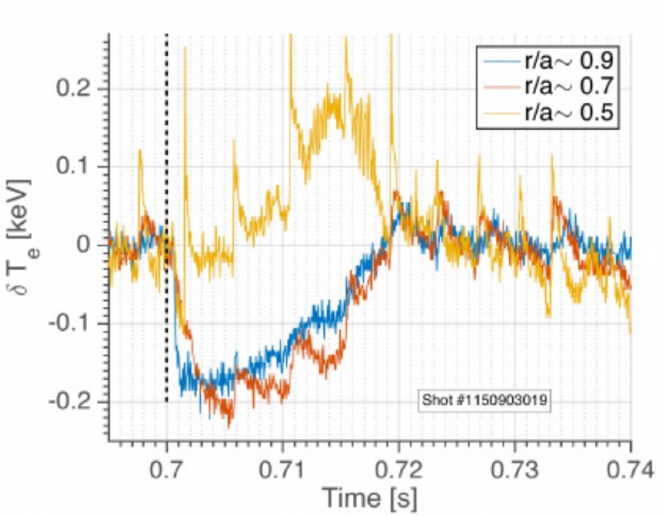




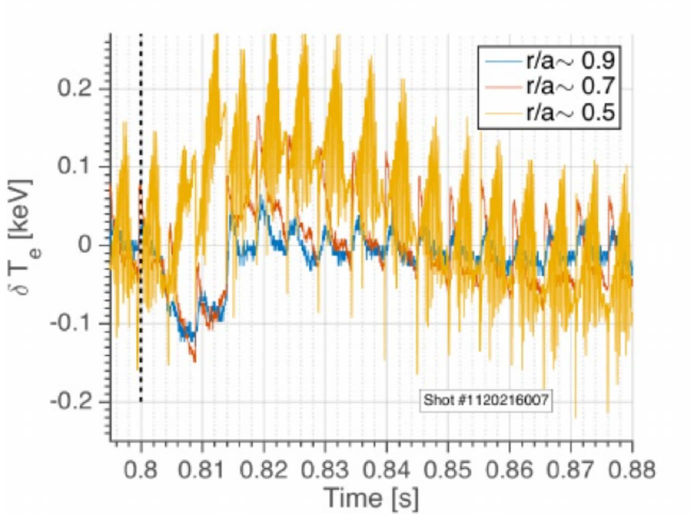
Temperature Inversions have complex dynamics



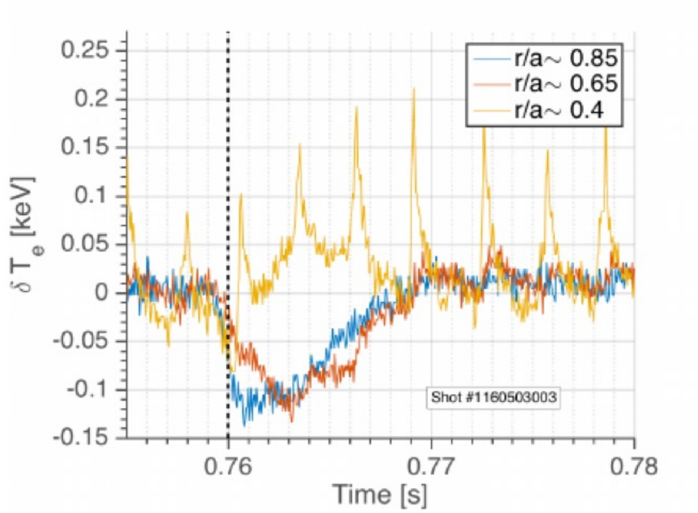
(a) LSN, Ohmic, $I_p = 550kA$, $< n_e >_{l04} = 0.6 \cdot 10^{20}/m^3$



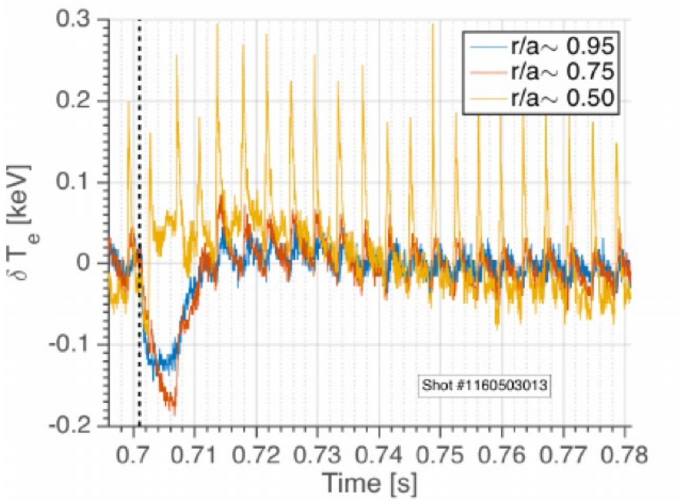
(b) LSN, Ohmic, $I_p = 800kA$, $< n_e >_{l04} = 0.53 \cdot 10^{20}/m^3$



(c) LSN, Ohmic, $I_p = 1,100kA$, $< n_e >_{l04} = 0.68 \cdot 10^{20}/m^3$

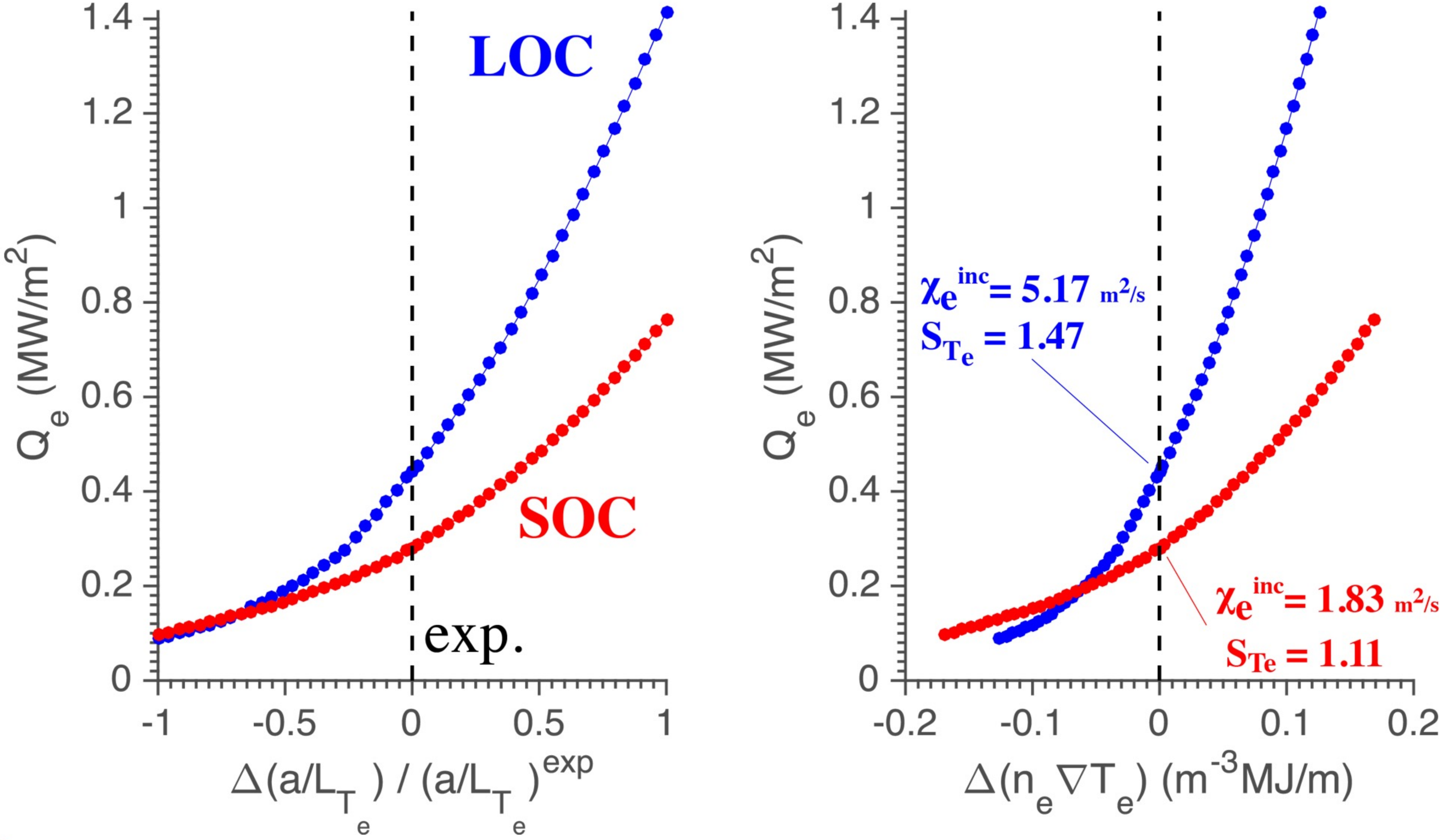


(d) LSN, $P_{RF} = 300kW$, $I_p = 550kA$, $< n_e >_{l04} = 0.53 \cdot 10^{20}/m^3$

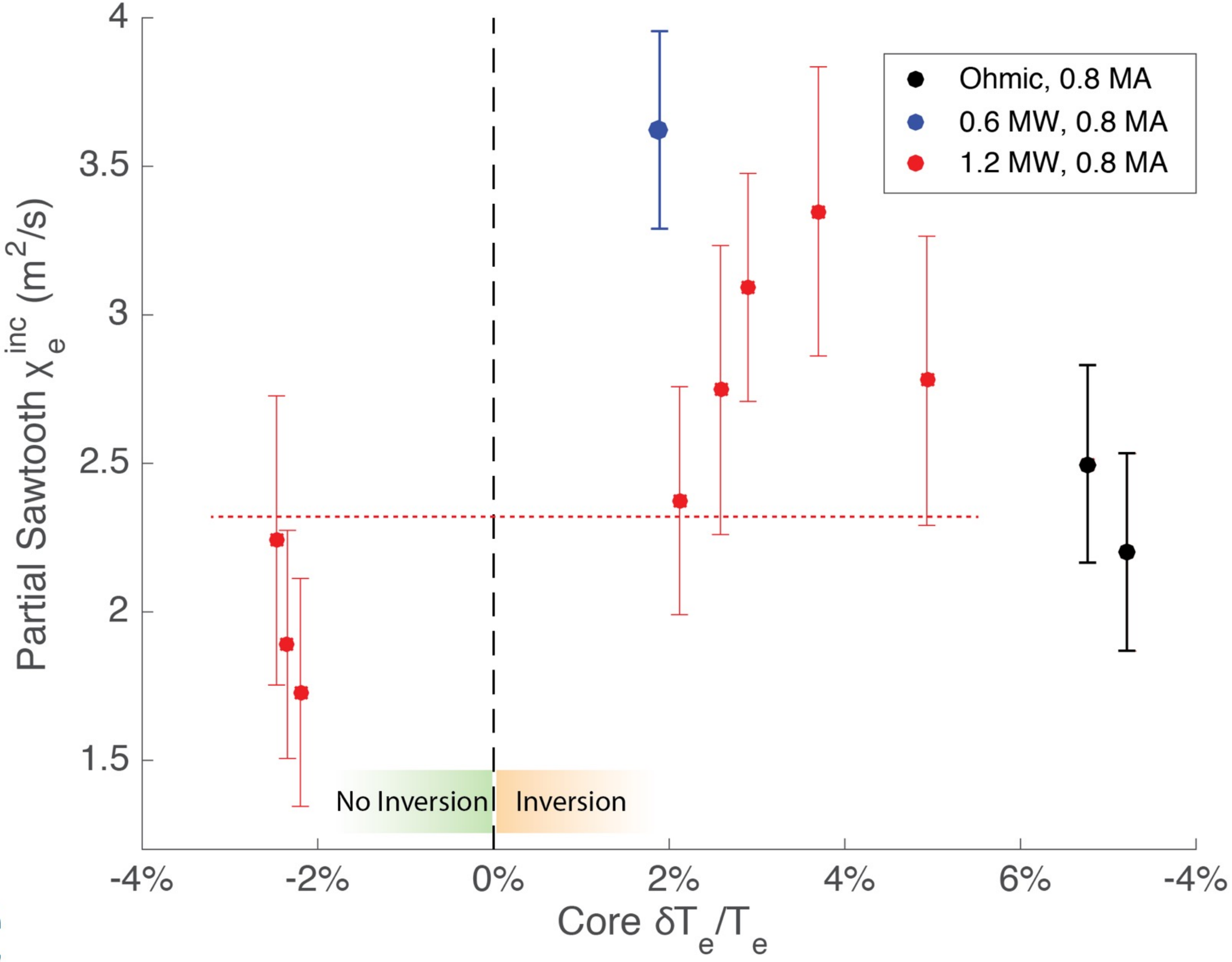


(e) LSN, $P_{RF} = 300kW$, $I_p = 800kA$, $< n_e >_{l04} = 0.6 \cdot 10^{20}/m^3$

TGLF does indeed capture a lower stiffness in SOC plasmas compared to LOC

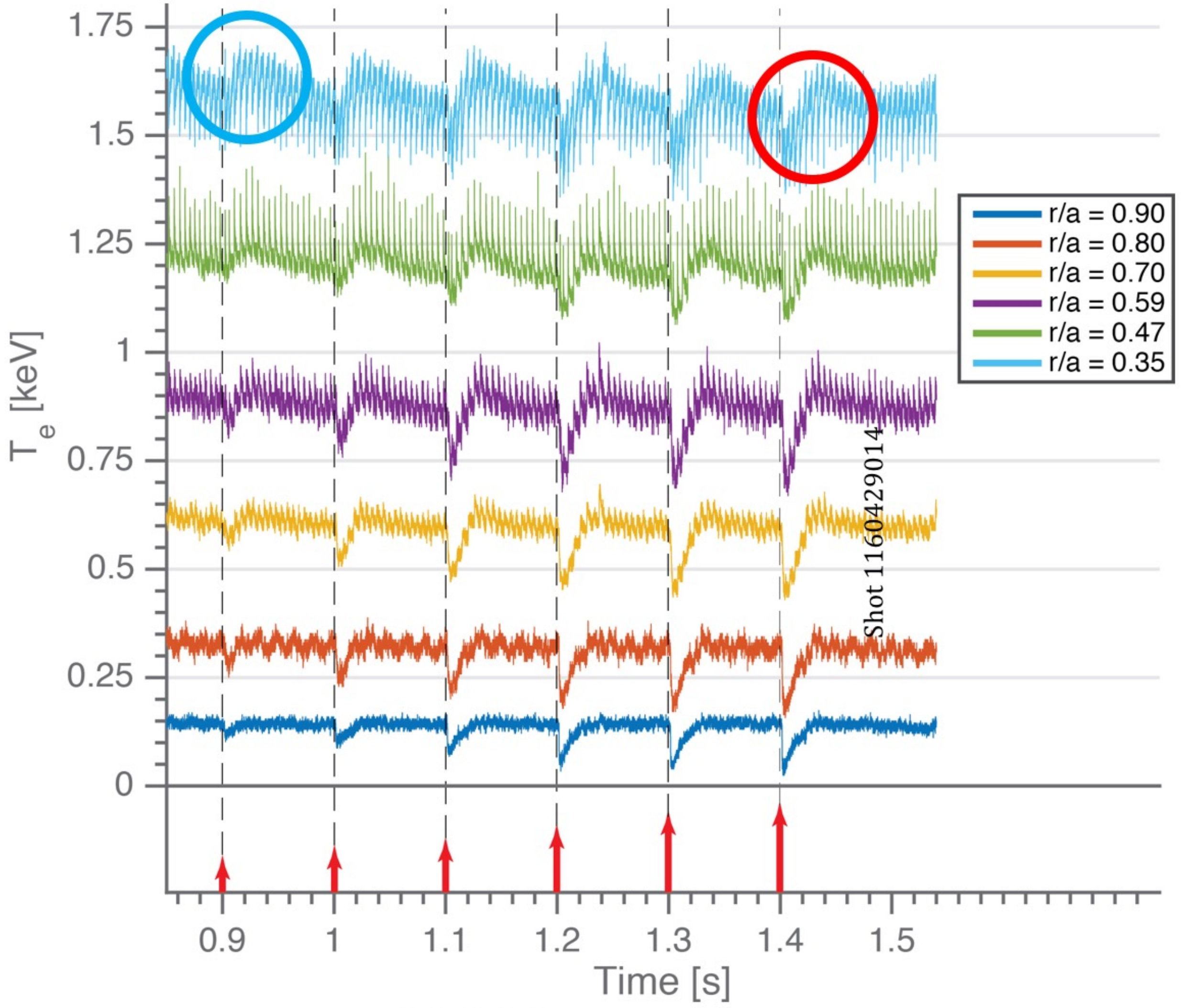


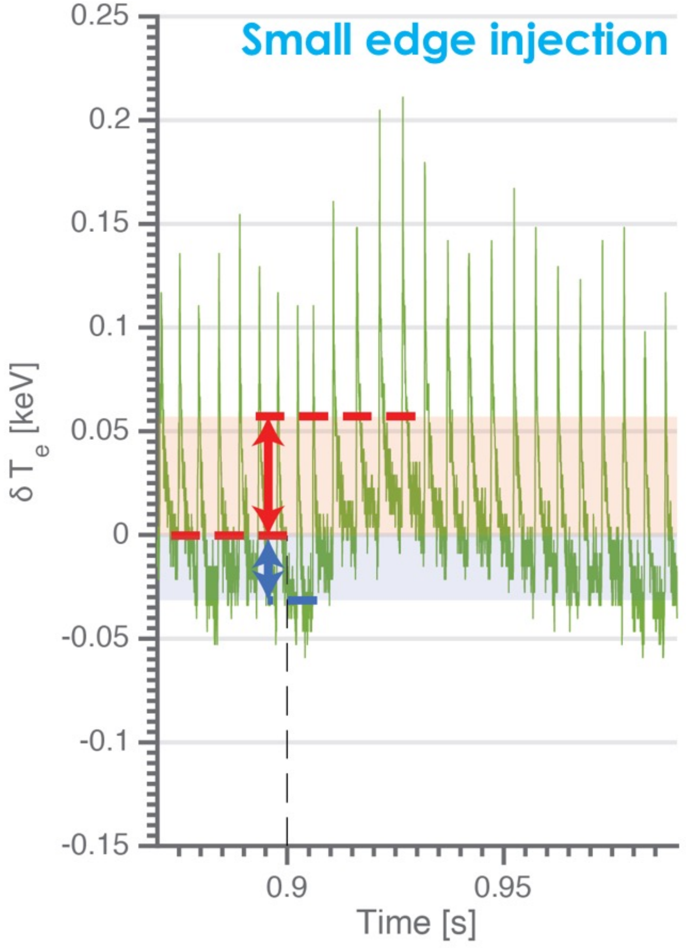
Experiments show that core temperature inversions take place in plasmas with higher stiffness

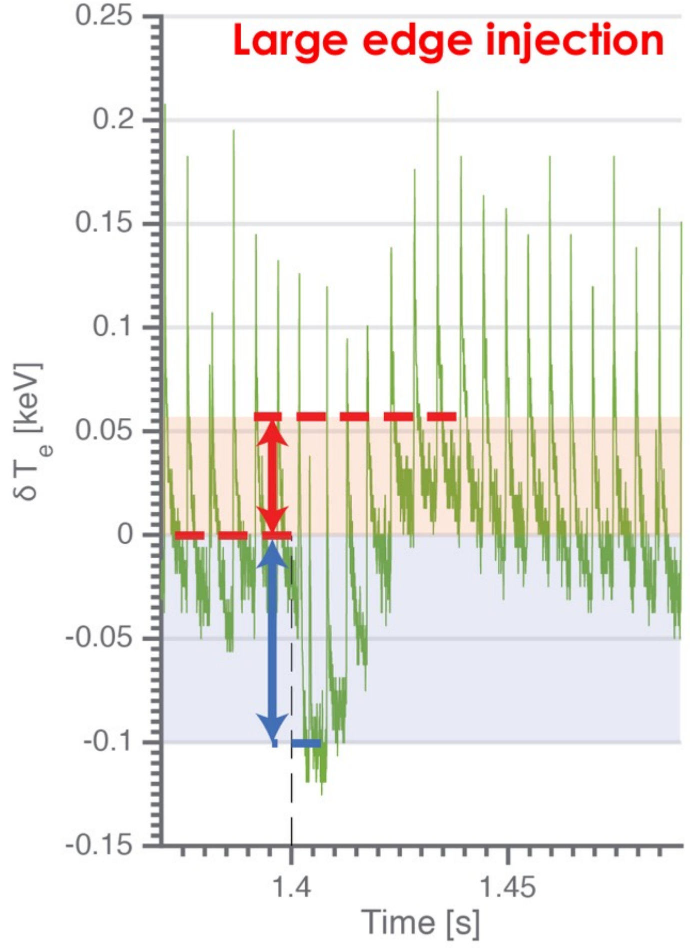


Observed mixing effect motivates new parameterization of T_e response

- LBO system at C-Mod allows multiple injections and controlled amount of impurities
- Mixing process: **Inward-propagating Edge cold-pulse + Temperature Inversion**

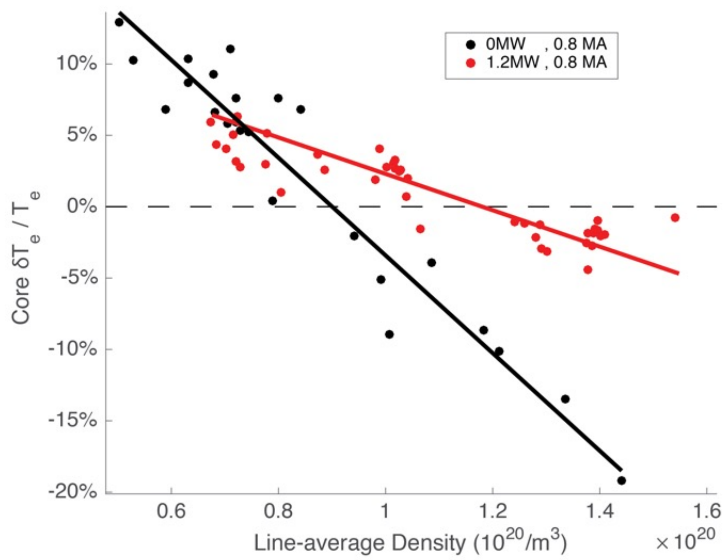


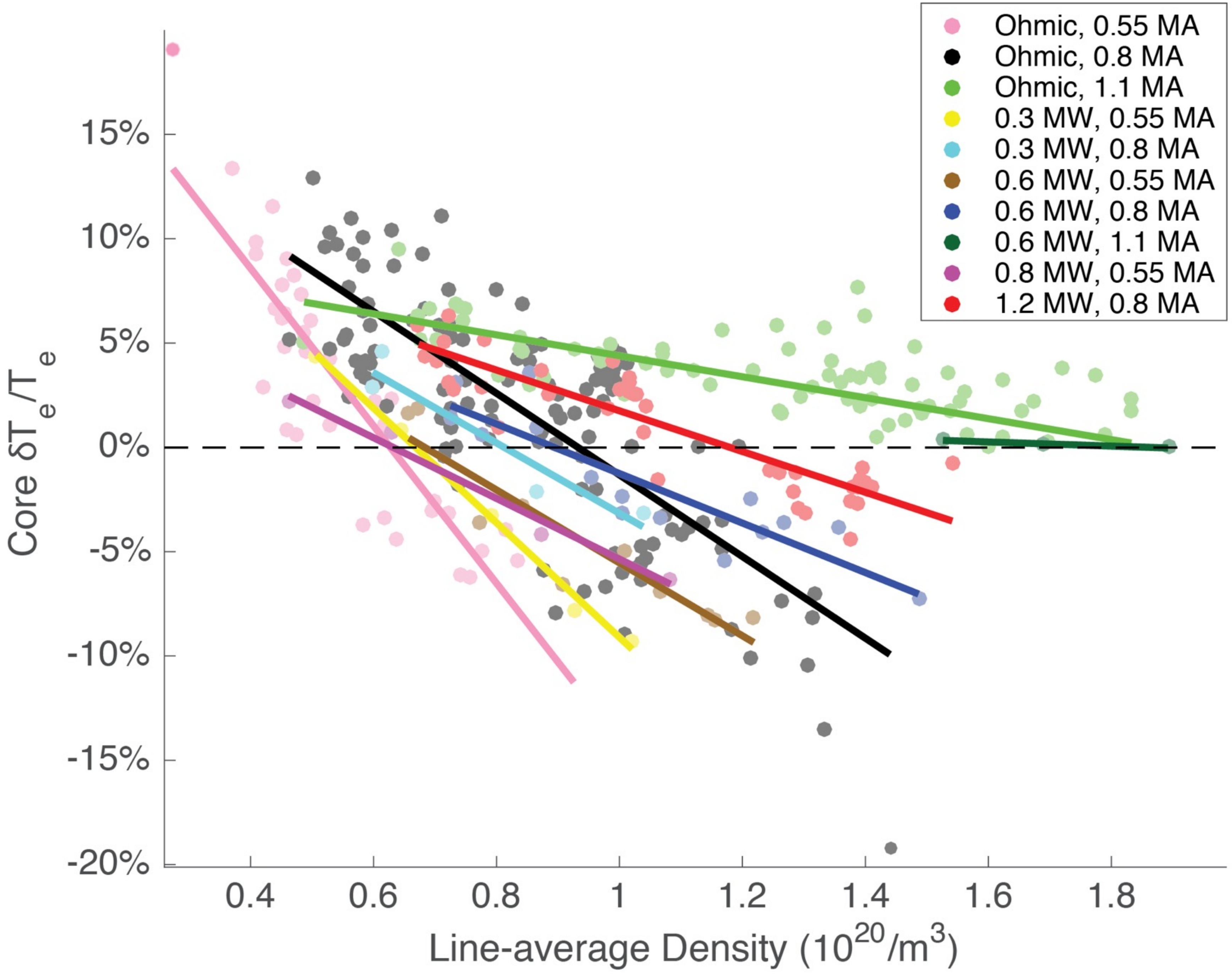




Perturbation amplitude depends on density & auxiliary heating

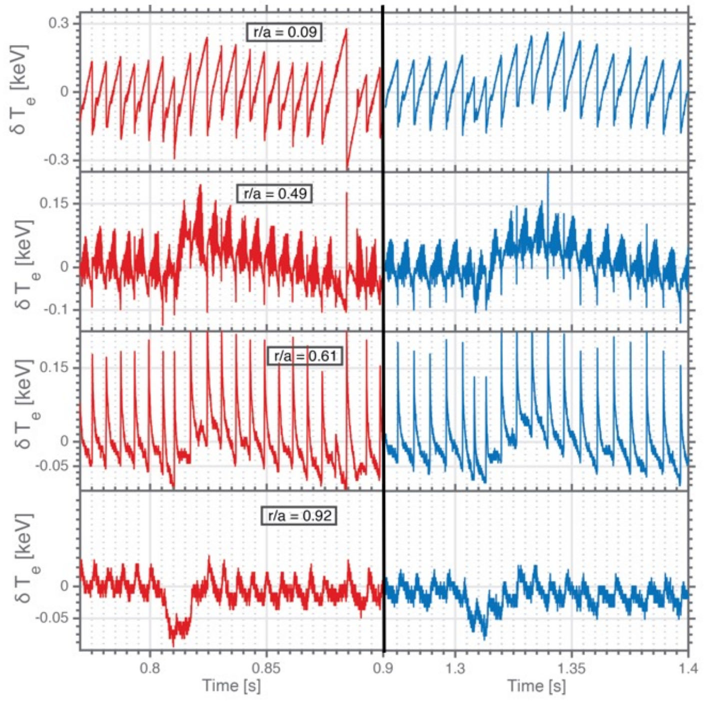
- Unique shot-by-shot analysis of 93 C-Mod plasmas (> 350 cold-pulses) reveals:
  - T_e Inversions happen at low $\langle n_e \rangle_l$
  - Core $\pm|\Delta T_e|$ depends on $\langle n_e \rangle_l$, I_p and P_{RF}
  - Thresholds in $\langle n_e \rangle_l$ depend on I_p and P_{RF}





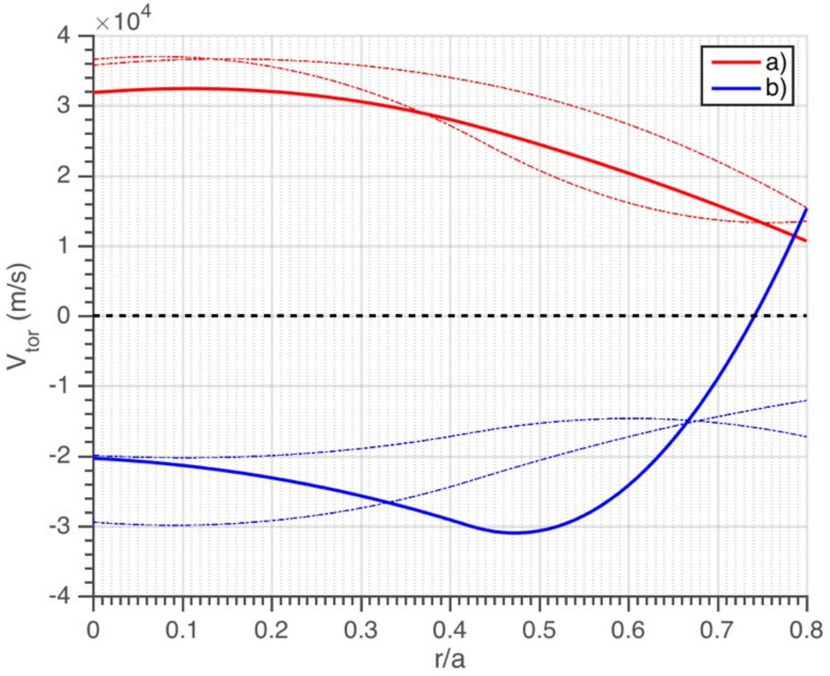
At ↑ I_p temperature inversions are observed when rotation has reversed

- At ↑ I_p, unified model for momentum & heat transport breaks up
- T_e inversions observed with both co-current and counter-current rotation



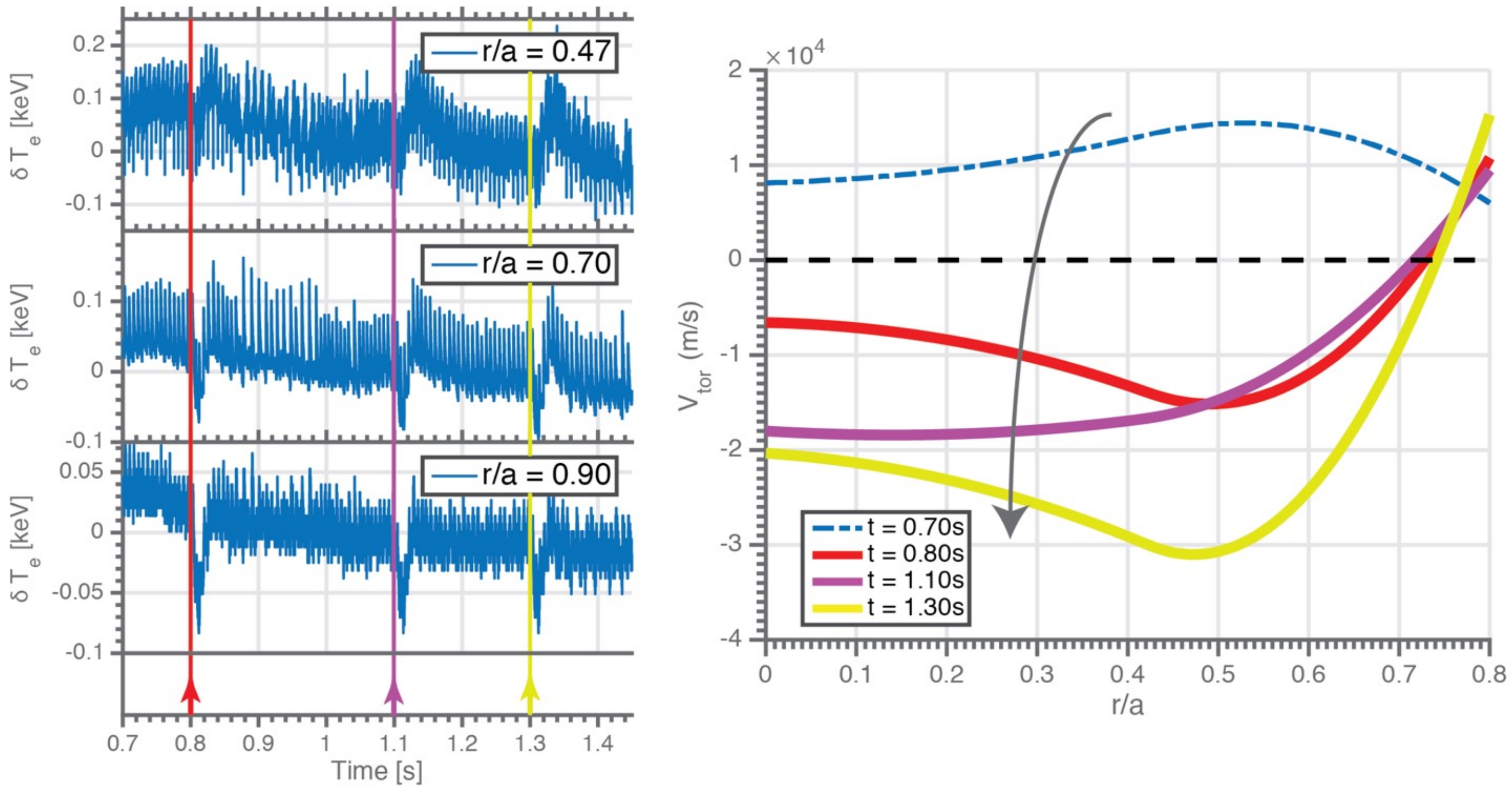
a) *Shot* 1120216017
1.1 MA, low density

b) *Shot* 1120216011
1.1 MA, high density



At ↑ I_p temperature inversions are observed when rotation has reversed

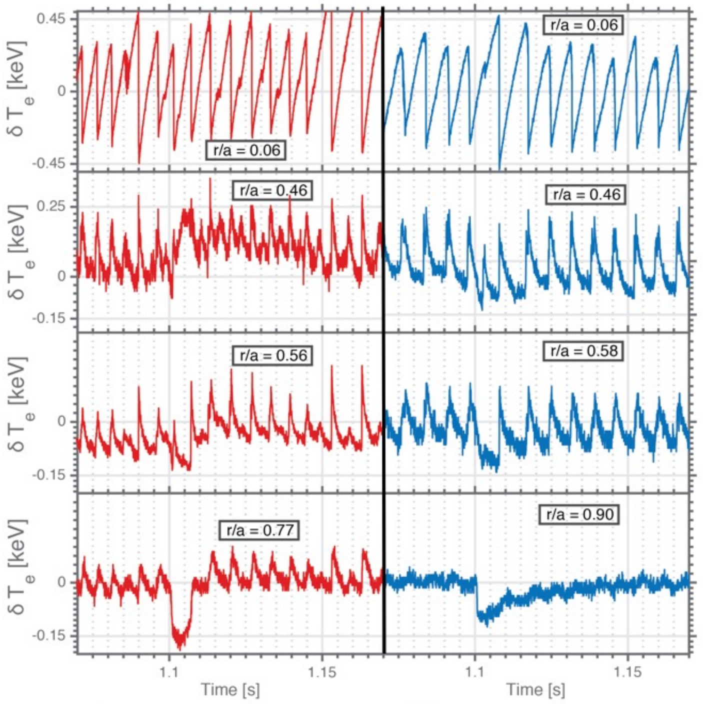
- Rotation reversal process does not change inversions behavior



Shot 1120216011

At ↑ P_{RF} temperature inversions disappear with co-current rotation

- Addition of RF power also breaks correlation
- T_e inversions and standard drops both observed with co-current V_{tor}



a) *Shot* 1150901021
0.8 MA, low density

b) *Shot* 1150901008
0.8 MA, high density