Review Article

Local Transport Dynamics of Cold Pulses in Tokamak Plasmas

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Abstract.
For over two decades, our fundamental understanding of energy transport dynamics in the core of tokamak plasmas had been challenged by the striking observation of temperature perturbation reversals following the injection of cold pulses at the plasma edge. These phenomena were first discovered by Gentle et al. [1] in 1995 and had long been suggested to be evidence of nonlocal transport effects. In recent years, a new explanation to these phenomena has emerged, fully consistent with the theory of turbulent transport in magnetized plasmas and in remarkable agreement with experiment. This article reviews the experimental observation of temperature reversals in tokamak plasmas and presents the explanation based on local transport physics.

1. Introduction

Understanding transport of energy, particle and momentum in the core of tokamak plasmas is key to the development of fusion energy. Performance of tokamaks is highly dependent on the temperature and density gradients attained in the plasma core, thus revealing the need of developing reliable and accurate models of neoclassical and turbulent transport to design new fusion devices and plan operational scenarios. Burning plasmas will soon be achieved in machines such as SPARC [2, 3] and ITER [4], and increasing efforts in the area of integrated modeling are being devoted to "predict-first" [5] scenarios that are both safe and efficient enough to achieve performance goals.

Key to integrated modeling of the plasma core is the understanding of turbulent transport dynamics, known to be the dominant contributor to energy losses in modern tokamaks. Turbulent energy transport has come a long way since it was first identified as the main source of anomalous transport, dramatically increasing transport levels from collisional, neoclassical theory predictions. The gyrokinetic theory of plasma turbulence is now widely considered to provide the appropriate theoretical framework to simulate turbulence in magnetically confined plasmas [6, 7], and has successfully explained many experimental observations of tokamak plasmas thanks to extensive validation exercises [8, and references therein].

Nonetheless, there are still some fundamental phenomena that remain unexplained. Until recently, one prominent example was the seemingly "nonlocal" temperature response of the plasma core to edge perturbations, originally described by Gentle et al. [1] and that had led to dozens of journal publications for over two decades [9, and references therein]. An example of such experimental observation is depicted in Figure 1a for a low-density Alcator C-Mod plasma, in contrast to the standard core temperature response at high density (Figure 1b). The observation of a fast (faster than energy confinement times) increase in the temperature of the core of the plasma caused by the cooling of the edge region (i.e. during a "cold-pulse" experiment) had long remained a mystery to be explained by modern turbulent transport theory. The expected locality of turbulent transport, owning to the small spatial scales of turbulent structures compared to the device size in modern tokamaks (radial correlation lengths of only a few ion gyroradii [10–14]), could not allow such reversal of the temperature perturbation, and therefore nonlocal effects seemed to be required to explain the full dynamics. In cold-pulse experiments, the magnitude of the core temperature rise is significant and with associated time scales shorter than an energy confinement time. Were nonlocal effects needed to explain it, modern turbulent transport theory and models would need to be revisited from the ground up, thus casting doubt on the accuracy of the predictions of burning plasmas in [15, 16] and ITER [17, 18] with theory-based transport models.

Recent experimental and computational work resulting from an international and multi-institution collaboration between the Alcator C-Mod [19, 20], DIII-D [21] and ASDEX Upgrade [22] teams has provided an explanation to the cold-pulse mystery without the need of nonlocal transport effects. Purely local transport models used nowadays to study and predict tokamak behavior are demonstrated to be enough to explain these effects, as long as multi-

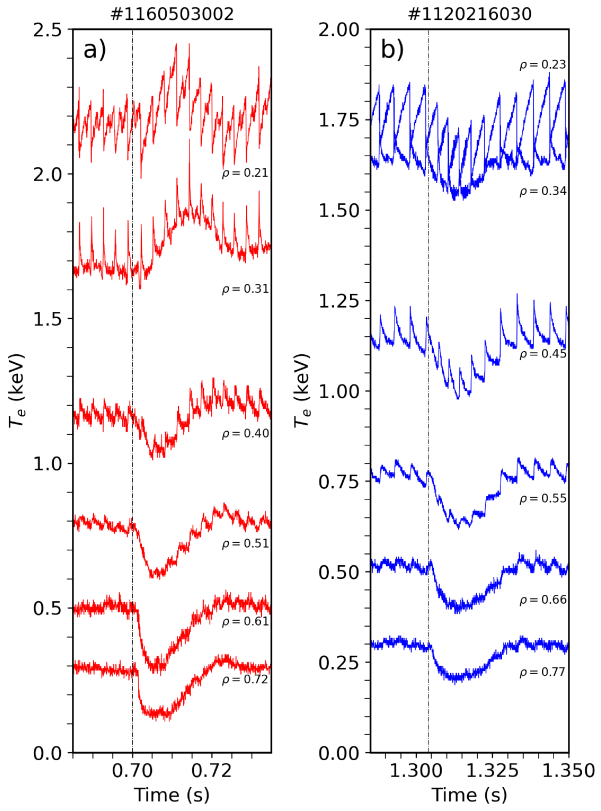

Figure 1. a) Example of temperature reversal effect in Alcator C-Mod in a low-density plasma, as measured by different channels of ECE diagnostic. b) Example of standard cold-pulse propagation at high density.

channel transport interactions are accurately captured within the model assumptions.

This paper provides a review of cold-pulse experiments and the local explanation for the temperature reversal effect. Section 2 provides a background of cold-pulse experiments and associated phenomenology. In Section 3, the local paradigm is presented, including past work, simulation results and quality of agreement with experiment. In Section 4, discussion and thoughts on the topic are provided. Lastly, in Section 5 we present a few final remarks.

2. Background

Impurity injections at the edge of magnetically confined plasmas have long been used for impurity transport studies [23–26]. When trace amounts of impurity neutral atoms are deposited at the edge of the plasma, they get ionized and transported inwards, reaching the central part of the plasma in a fast time scale. Once these impurity ions reach the plasma core, the time evolution of the concentration of impurity charge states as they decay back to background levels can be used to characterize impurity transport via inference frameworks [27] and forward particle transport models, such as STRAHL [28] and Aurora [27].

When larger amounts of impurities are introduced, the local increase of electron energy losses via ionization and radiation at the plasma edge can drive a sharp drop in temperature [29]. This "cold pulse" in temperature can propagate inwards, thus serving as a useful tool to survey local heat transport dynamics throughout the entire plasma core. Characteristic elements of energy transport such as electron heat stiffness and pinch radial profiles can be inferred by analyzing the time traces of the plasma response to temperature perturbations [30].

Not long after the first utilization of perturbative impurity injections to examine electron heat transport dynamics, the phenomenon of "core temperature reversal" was identified in the TEXT tokamak [1, 31], as shown in Figure 2. Characteristic of low-density plasmas, these effects were considered evidence of the existence of "nonlocal" transport [32], due to the apparent difficulty of local, diffusive models to reproduce the speed of propagation and features of the phenomenon. Far from being an isolated observation from the TEXT tokamak [1, 31, 33], these temperature reversal effects were readily reproduced in many other tokamaks and stellarators, with studies that have spanned more than two decades and have included, to the authors' knowledge, over a dozen of fusion devices: TFTR [34, 35], RTP [36–38], Tore Supra [39, 40], ASDEX Upgrade [22, 41], JET [42], LHD [43–50], HL-2A [51–57], Alcator C-Mod [19, 21, 30, 58, 59], KSTAR [60, 61], J-TEXT [62, 63], DIII-D [20], EAST [64], and ADITYA-U [65].

2.1. Evidence as a transport phenomenon

Soon after their discovery, certain explanations for the temperature reversal effect were discarded based on experimental observations and basic intuition on spatial and time scales of plasma phenomena. Increased Ohmic heating in the plasma core as a consequence of current redistribution could not be possible, as well as changes in the local q-profile. Experiments in TEXT [1, 31] showed no evidence of an increase in central current density or changes in Joule heating. Not only the current redistribution time scales are much longer than the observed temperature effect, but also such redistribution could cause the onset of sawteeth or significant variations in the plasma internal inductance, which were not observed experimentally. Furthermore, the later evidence of such effects in stellarators means that the phenomenology cannot be mediated by the current density [33]. Changes in the effective ion charge required to account for the change

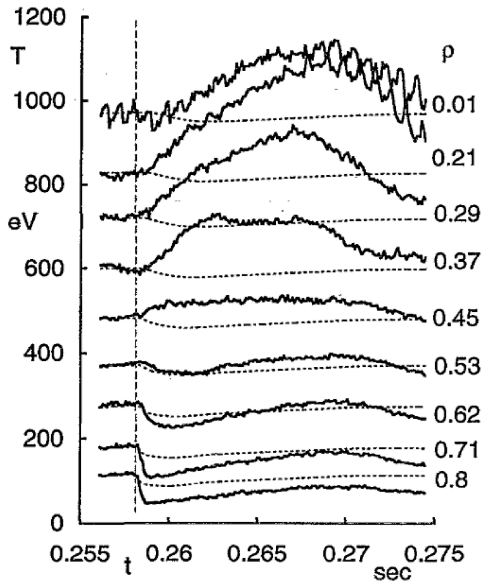

Figure 2. Core temperature evolution following the cold pulse injection at the edge in the TEXT tokamak (solid), and predictions from a standard transport model (dashed). Reproduced from [31], with the permission of AIP Publishing.

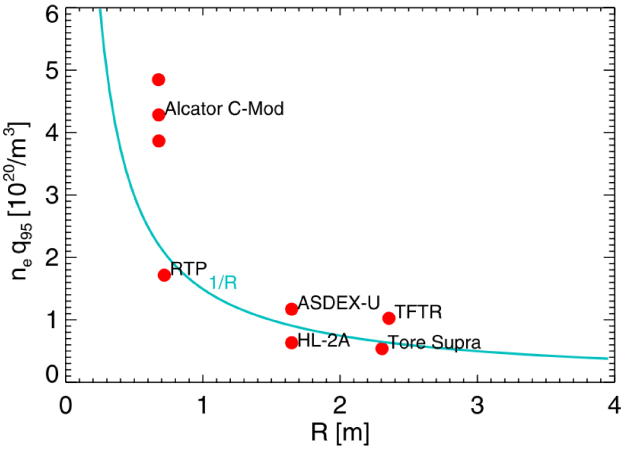

Figure 3. Transition metric from temperature reversals to standard temperature drop for a number of fusion devices (collected from [35, 37, 39, 41, 54, 58]). Reproduced courtesy of IAEA. Figure from [30]. Copyright 2014 IAEA.

in resistivity needed for the core temperature heating would need to be much larger than those observed and inferred (through loop voltage measurements) experimentally, and certainly the amount of neutral impurities injected at the edge of the plasma would need to be much larger [1, 31]. The lack of heating power redistribution as a possible cause of these effects was also studied in Tore Supra [39], which again showed no evidence of such in discharges heated by lower hybrid waves.

Changes in plasma position and magnetic flux surfaces could compromise diagnostic measurements, and therefore they were studied early on [1, 31, 34]. Measured changes in plasma position and flux surfaces were negligible for the cold-pulse experiments studied. The effect of suprathermal electrons compromising temperature measurements from electron cyclotron emission (ECE) diagnostics was also discarded after analysis of Tore Supra experiments [39].

Presence of MHD modes (already existing or triggered by the cold pulse) could affect transport properties and were also considered as candidates. Experiments in Tore Supra [39] and LHD [45] showed no significant changes in the amplitude of low-m MHD modes during the temperature reversal phenomenon. Work in Alcator C-Mod [58] indicated that no tearing modes were seen during the cold-pulse experiments, likely discarding the effect of magnetic islands on transport as a mechanism for the temperature reversal.

In conclusion, all experimental evidence gathered over the years seemed to suggest that the temperature reversal had to be a transport effect through fast changes to core electron heat diffusivity, χ_e. The question of which parameter (and where in the plasma) caused a significant change to electron heat transport properties with the right time scales was the big conundrum that had largely remained unanswered for over two decades.

2.2. Effect of density and plasma current

One of the most agreed upon observations of the phenomenology of the temperature reversal phenomenon is its strong dependency on density. Either through a smooth decrease of the temperature reversal magnitude, or by a sharper transition, all machines have observed the disappearance of the temperature reversal effect when increasing the average plasma density. Oftentimes, the linear scaling of the temperature reversal with density was better characterized when a $T_e^{-1/2}$ factor was included. Such scaling was required to include discharges at different plasma current and heating schemes [34, 41]. Experimental studies in Alcator C-Mod [30, 58] proposed a normalized collisionality dependence to explain the density and plasma current scalings. The ratio of the electron-ion collision frequency and the bounce frequency of trapped electrons simplified [30] as:

$$\nu^* = \frac{\nu_{ei}}{\epsilon\omega_{be}} \propto \frac{qRZ_{eff}n_e}{T_e^2\epsilon^{3/2}} \propto n_e qR \propto \overline{n}_e q_{95} R_0 \qquad (1)$$

was able to bring together observations from different tokamaks. Here, $\overline{n}_e$ is the line-averaged density, q_{95} is the safety factor at the 95% poloidal flux surface, and R_0 is the device major radius. In Equation 1, it was assumed that the factor $\left(Z_{eff}/T_e^2\right)$ is roughly

constant, and that the aspect ratio is similar for the tokamaks included in the study. Figure 3 collects observations from different tokamaks [30], revealing that the transition to standard temperature drop depends on $\overline{n}_e q_{95} R_0$.

Importantly, experiments in RTP [36–38], ASDEX Upgrade [41] and Alcator C-Mod [58] demonstrated that the radial location of temperature profile "flex point" was affected by the plasma current. In particular, the flex point moved outwards (higher radii) with increased plasma current, suggesting some connection with the structure of the q-profile.

2.3. Effect of external heating and collisional equilibration

While temperature reversals are mostly characteristic of low-collisionality Ohmic plasmas, they have been observed with different levels of auxiliary heating. TEXT experiments [33] showed that the temperature reversals got weaker with the addition of electron cyclotron heating (ECH) power, and experiments with neutral beam injections (NBI) in TFTR [35] and JET [42] showed no temperature reversals in such ion-heating dominated plasmas. Experiments in Tore Supra [39] observed, however, that temperature reversals were more present in discharges heated by lower hybrid (LH) waves, and studies in ASDEX Upgrade [22, 41], RTP [38] and HL-2A [53, 54] showed that ECH had actually a positive effect in increasing the magnitude (and range of existence) of temperature reversals.

It has long been suggested [32] that the temperature reversal phenomenon is closely related to the electron-ion power transfer. Consistent with the observation of the collisionality dependence from Equation 1, past studies [32, 37, 42], have noted that the effects take place when the ratio of collisional electron-ion power transfer to electron heat conduction is sufficiently small (i.e. thermally decoupled electrons and ions). Experiments in ASDEX Upgrade [22] with Ohmic, ECH- and NBI-heated plasmas at different densities found that the core temperature perturbation was strongly dependent on the electron to ion heat flux ratio (Q_e/Q_i) at mid-radius.

2.4. Connection with other transport phenomena

The appearance of these effects in low-collisionality, non ion-heated plasmas suggested somehow a relationship with linear Ohmic confinement (LOC) characteristics, and the disappearance of the reversals at high density seemed to be correlated with the transition to saturated Ohmic confinement (SOC) [58, 66]. In fact, the intrinsic rotation reversal phenomenon [67, 68] has been hypothesized to play a role in the transport dynamics that could modify the core electron temperature response. Experiments with Ohmic plasmas in Alcator C-Mod [30, 58] and with ECH plasmas in KSTAR [61] showed that the disappearance of the temperature reversal was concomitant to the reversal of intrinsic toroidal rotation.

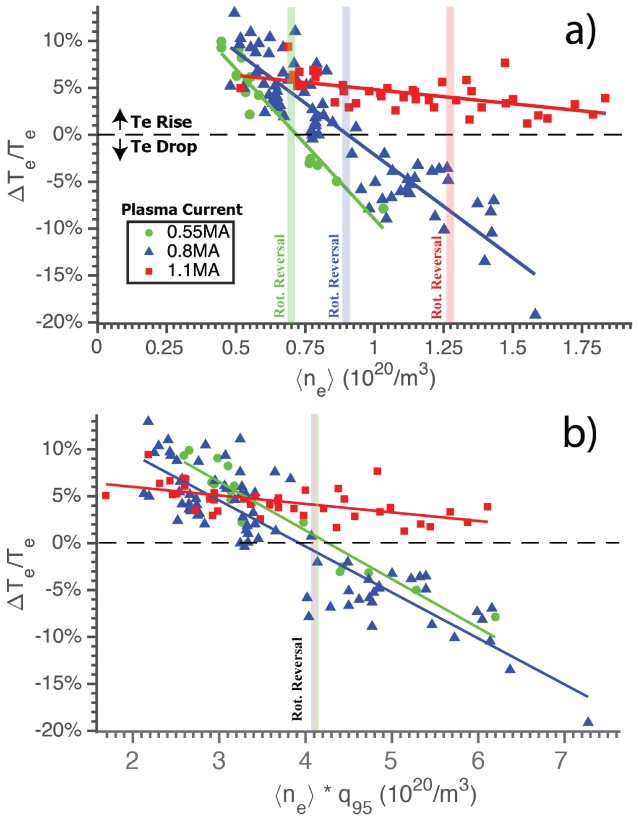

Figure 4. Change in core electron temperature for different plasma currents as a function of (a) line-average density and (b) collisionality metric. Reproduced courtesy of IAEA. Figure from [59]. Copyright 2017 IAEA.

More recent work in Alcator C-Mod [59] demonstrated, using a large database study, that temperature reversals occur regardless of the direction of the intrinsic toroidal rotation (including in locked-mode, zero-rotation plasmas), which challenged the idea that these energy transport effects could be connected somehow to momentum transport phenomena. Figure 4 depicts a database study of core temperature perturbations and intrinsic rotation reversals. At high current (I_p = 1.1MA in Alcator C-Mod), the intrinsic rotation reversal had no effect on the behavior of the core temperature perturbations: temperature reversals occurred with both co- and counter-current toroidal rotation.

2.5. Nonlocal modeling of cold-pulse propagation

In parallel to the study of cold-pulse propagation with local models, which will be the focus of the remaining of this review, several theories based on nonlocal models have been suggested, and the reader is referred to a companion publication for details on this topic [69].

In the context of nonlocal transport, the experimental observation of the fast temperature reversal phenomenon suggests that prompt changes in thermal diffusivity leading to the increase in core temperature are caused by changes in the outer region [70]. It is proposed that mechanisms such as meso- and macro-scale fluctuations, energetic particles effects and turbulence spreading mechanisms could cause the connection between interior and outer plasma regions, even if they are separated by many micro-turbulence scale lengths. From these, the turbulence spreading model has been prominent in the literature of nonlocal explanations to the cold-pulse phenomenon [71, 72] and has been compared qualitatively to experimental observations [62, 63, 73]. By this mechanism, coupling of distant regions can be possible due to fast spreading in the turbulence intensity field, which in principle can be independent from local plasma parameters and gradients. Another notable model discussed in the literature is the fractional diffusion model [74], which utilizes transport operators that can make the heat flux at a given point depend on nonlocal contributions from distant regions or on global properties of the temperature profile.

While we recognize that such models can provide the basis for the fast propagation and reversal of cold pulses in tokamak plasmas, in this review paper we focus our attention on the local explanation to the cold-pulse phenomenology, as it has shown agreement with many experimental observations of the effect. And more importantly, it was able to reconcile the widely used and validated local drift-wave turbulent transport theory with the fast cold-pulse propagation, without the need of additional or different transport mechanisms. The reader is invited to read more details about nonlocal transport explanations in Ref [69].

3. The local paradigm

As described in Section 2, temperature reversals have broadly been considered as a consequence of transient changes in background energy transport. Most models to explain the temperature inversions were phenomenological [1, 30, 31, 33, 34, 38]. In this context, a phenomenological model consists of ad-hoc modifications to the local diffusivity (or, in some cases, the local electron heat pinch [30]) so as to cause the temperature reversal. However, such models generally shift the problem from "*What causes the fast temperature reversal?*" to "*What causes the fast electron heat transport reduction?*" In other words, the changes in transport coefficients that would be required to produce a temperature reversal of the right magnitude and with the right time scale may be inconsistent with the underlying physics that dictates neoclassical and turbulent transport properties in a self-consistent manner.

3.1. First studies of local transport effects

Before the full explanation that was recently provided by the Alcator C-Mod [19, 20], DIII-D [21] and ASDEX Upgrade [22] teams, there have been a few other studies that pioneered the use of local transport models to explain the temperature reversal effect. However, the lack of accurate physics models to simulate turbulent transport dynamics at the time prevented the achievement of a full explanation for the experimental observations. Furthermore, in these first studies, multi-channel interactions (those related to the effect of the transient density gradient flattening on electron heat transport) were not properly accounted for. These were found to be key in later work, as it will be discussed in following sections.

Kinsey et al. [75] first proposed the use of local models (in particular, stiff critical gradient models) to simulate computationally the core temperature response to edge cold pulses. Simulations with the IFS-PPPL model [76] reproduced a qualitative reversal of core temperature, mostly as a consequence of the effect of T_i/T_e on ion temperature gradient (ITG) stability that followed the cold-pulse injection. Quantitative match of steady-state kinetic profiles and the magnitude and time scale of the cold pulse propagation and reversal magnitude still remained largely elusive. Similar modeling of cold pulses in ASDEX Upgrade by Ryter et al. [41] also yielded qualitative agreement, but the edge perturbation required for a moderate reversal was much larger than in experiment. Finally, simulation work by Mantica et al. [42] of JET discharges also showed the possibility of temperature reversals with local physics, although the ion transport dynamics had to be modified for the effect in the electron channel to appear.

3.2. Improved quasilinear modeling

Building from previous work, simulations with local models within flux-matching (i.e. integrated modeling) frameworks were revisited after two decades of developments in quasilinear transport theory and computational techniques. Simulations of cold pulses in Alcator C-Mod [19, 20], DIII-D [21] and ASDEX Upgrade [22] were performed using the Trapped Gyro-Landau Fluid (TGLF) quasilinear transport model,

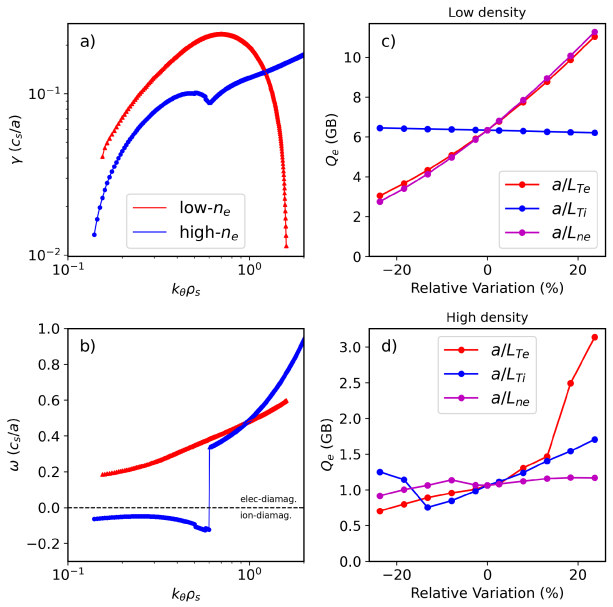

Figure 5. On the left, ion-scale (a) linear growth rate and (b) real frequency spectra for characteristic low and high density Ohmic plasmas in Alcator C-Mod, as calculated with the gyro-fluid TGLF model. Modes with $\gamma < 0.01 c_s/a$ have been removed for plotting purposes. On the right, scans of driving gradients for the (c) low- and (d) high- density cases. Heat fluxes are calculated using SAT-1. In low-density Ohmic plasmas, the main microinstability in the plasma core is TEM, which depends strongly on electron temperature and density gradients. At high density, ITG becomes dominant at low-k ($k_\theta\rho_s < 0.6$), and density gradients do not have a strong effect on electron heat transport.

which models turbulence saturation via zonal flow mixing (SAT-1 rule).

The TGLF model [77, 78] solves an electromagnetic, linear, gyro-fluid set of equations for multiple plasma species to find the unstable drift-wave-type modes in the core of tokamak plasmas. It is suited to capture trapped ion and electron modes (TIM, TEM), ion and electron temperature gradient modes (ITG, ETG) and kinetic ballooning modes (KBM). One of the cornerstones of TGLF is its ability to capture trapped particle dynamics more accurately compared to the original gyro-Landau-fluid (GLF23) transport model [79]. This made TGLF a great candidate to explore cold-pulse dynamics. Given the low collisionality that characterizes experiments that exhibit temperature reversals, it is expected that TEM-like turbulence is one of the main contributors to electron heat transport in the plasmas of interest. In TGLF, a saturation rule is used to find the saturated level of potential fluctuations that may result from the linearly unstable modes. Saturation rules are constructed using databases of fully nonlinear gyrokinetic simulations, and one of the latest saturation rule (SAT-1) [80, 81] was demonstrated to successfully model the physics of the nonlinear upshift of the critical gradient (Dimits shift) [82] and multi-scale coupling effects [83–85]. Validation studies of TGLF SAT-1 (e.g. [86]) have shown improved accuracy with respect to previous gyro-fluid solvers and previous saturation rules.

Integrated transport simulations with the TRANSP [87] and ASTRA [88] power balance frameworks were used to study the cold pulse behavior. TGLF SAT-1 was used to calculate the self-consistent time evolution of the turbulent electron and ion heat diffusivities following the cold pulse injections. In steady-state, conditions that exhibited temperature reversals were dominated by TEM modes at long wavelengths, which emphasized the need to include accurate trapped particle physics in the turbulence simulations to explain cold-pulse dynamics. Figure 5 depicts characteristic turbulence spectra for low and high density conditions that exhibit temperature reversals and diffusive drops respectively. At low density, the presence of TEMs causes the electron heat flux to be sensitive to the variation of density gradients. Linear ion-scale gyrokinetic simulations confirmed the same results as the gyro-fluid modeling [30]: at low density, the plasma core sits in a TEM-dominated regime, sensitive to density gradients, while the high-density plasma becomes more sensitive to ion temperature gradients.

3.3. The effect of density gradients

To introduce cold pulses at the edge of otherwise stationary plasmas, actuators that inject particles into the plasma are used. The most typical actuator used for such experiments is the laser blow-off (LBO) technique, but others such as transient gas puffs (e.g. [65]), pellets (e.g. [37]) or super-sonic molecular beam injections (SMBI) (e.g. [54]) have been used. The injection of neutral particles come with an associated increase in radiation and ionization losses, as well as a possible decrease in plasma average temperature as a consequence of equilibration of the plasma with the "colder" impurity ions (i.e. via an isobaric process). LBO injections have the advantage of the localization of the impurity source at the edge, if a proper impurity species is used.

One main consequence of the injection of cold pulses in tokamak plasmas is the unavoidable perturbation of background density profiles. Such perturbations have been reported in many devices. For example, pellet injections in RTP [37] that displayed temperature reversals had a large associated increase in electron density (reaching up to 40% the background density), as inferred from the inversion of interferometer measurements. SMBI experiments in J-TEXT [62] showed changes in density of about 10%, and LBO injections in Alcator C-Mod [30] showcased changes on the order of 30% in average

electron density. Recent work with gas puffs in ADITYA-U [65] observed increases in electron density of about 15%-20%, and reported a flattening of the core density profile. Because the change in electron density does not happen in a self-similar way, density gradient scale lengths can widely vary throughout the propagation of the cold pulse from the edge to the core. Because it is recognized that drift-wave-type turbulent transport is affected by density gradients (especially in low-collisionality TEM-dominated plasmas), the observation of changes in density profiles during the cold pulse propagation was a clear indication that multi-channel transport effects were required if local physics was to be successful in explaining the intriguing temperature reversals.

3.4. Heat transport simulations

Simulations with only energy transport prediction required the evolution of a density perturbation for the temperature reversal effect to appear in simulations. In Alcator C-Mod [19], fast interferometer data indicated the possible propagation of a density pulse that followed the cold pulse injection at the edge, but the spatial profile of the perturbation was unclear at the time. Dedicated experiments in DIII-D [20] demonstrated, thanks to high time and spatial resolution density profile reflectometry, that a density pulse originated at the edge and propagated inwards, reaching the core in a very fast time scale. The evolution of the electron density pulse was consistent with the evolution of the impurity profile as given by the STRAHL code [28] and with experimentally inferred diffusion and convection impurity transport coefficients. ASDEX Upgrade experiments also measured a significant perturbation to the electron density, determined via the integrated data analysis suite (IDA) [89].

When a density pulse propagates from edge to core in a monotonically increasing density profile (as it is often the case in the core of tokamaks), a reduction of density gradients at the front of the density pulse is always present. A reduction of density gradients in plasmas with density-gradient driven turbulence comes with an associated reduction of transport levels, and can be understood as a stabilization (or a transient transport barrier) effect. This is precisely what was first observed in simulation work of Alcator C-Mod cold-pulse experiments [19], when, for the first time, the impact of the density evolution was taken into account in the modeling of the temperature response. The TGLF model successfully captured the stabilization of linear, mid-k TEM modes in the plasma core, as a manually imposed density pulse propagated from edge to core. From a quasilinear point of view, a reduction of the linear growth rate will cause a decrease

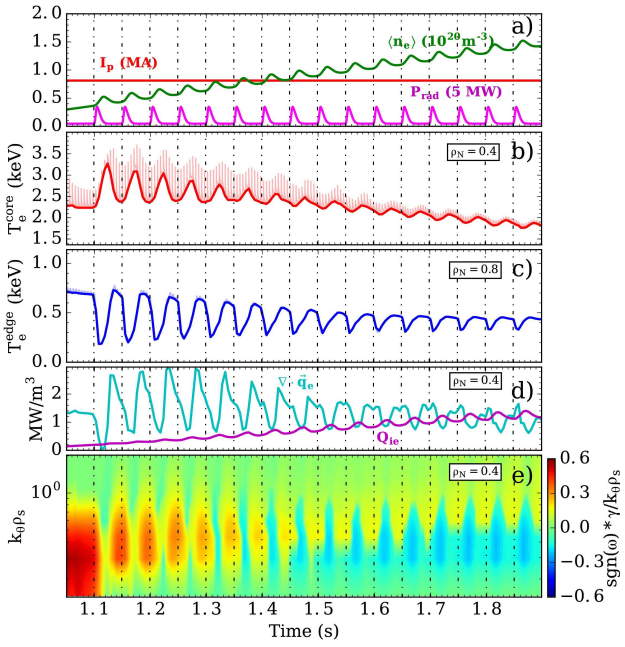

Figure 6. Simulation of density scan with multiple cold-pulse injections in an Alcator C-Mod plasma. Quantities in plots: Plasma current, volume-averaged density and total radiated power; edge and core electron temperature traces; electron–ion collisional power and electron conducted power at $\rho_N = 0.4$; and low-k linear growth rates spectrum at $\rho_N = 0.4$, with sign representing direction of propagation (blue: ion diamagnetic direction; red: electron diamagnetic direction). Reproduced courtesy of IAEA. Figure from [21]. Copyright 2019 IAEA.

of potential fluctuations and thus lower transport levels. This dynamics can be observed in Figure 6, which depicts the core plasma behavior following the edge perturbations. At low density (left part of the figure), the density pulse causes the reduction of linear growth rate of electron modes, thus reducing heat flux, allowing the temperature to increase (evoking what can be understood as a transient heat transport barrier).

This phenomenology was observed in the simulations, and was used to predict-first experiments in the DIII-D tokamak [20]. Near quantitative match of the magnitude of the temperature reversal in DIII-D (a machine that had never reported temperature reversals in the past) was achieved, evidencing the superb predictive power of the TGLF model. In the DIII-D study, it was determined that not only the reduction of the electron density gradient caused the reduction of electron heat transport levels, but also the increase in impurity content and reduction of impurity density gradient also contributed to TEM stabilization. Increased collisionality and effective ion charge also contributed, but their effect was not very strong given the small variation of these parameters during the cold-

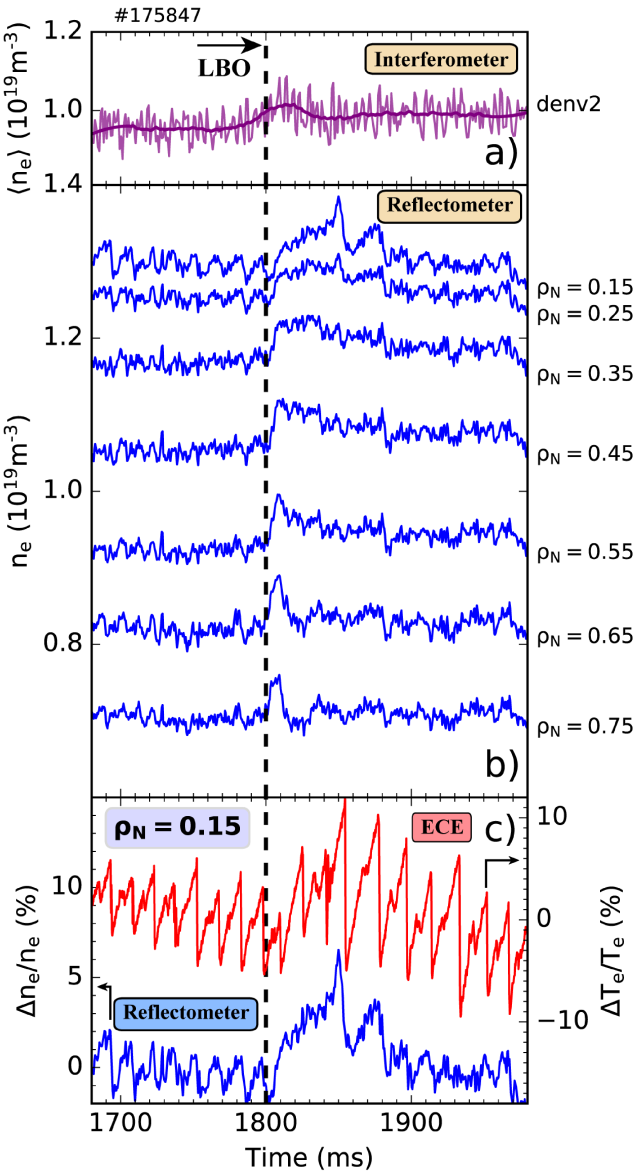

Figure 7. (a) Line-average density, (b) local density and (c) core electron temperature and density as measured during cold-pulse propagation in DIII-D. Reproduced from [20], with the permission of AIP Publishing.

pulse propagation.

High time resolution density profile reflectometry in DIII-D [90] was used to confirm the existence of a density pulse that propagates from edge to core, as depicted in Figure 7. When such a measured pulse was fitted to a skewed Gaussian pulse and introduced in simulation, excellent match of the time traces of the temperature perturbation were obtained. This was further confirmation that the density pulse propagation from edge to core, as measured, was capable of producing temperature reversals with the right magnitude and time scale, and conclusively confirmed that a local transport model of heat transport was enough to reproduce the temperature reversal phenomenon. In fact, this work reconciled the steady-state prediction of kinetic profiles based on standard heat diffusion equations, with the much faster propagation of the cold pulse from edge to core.

3.5. Particle transport dynamics

Experimental and simulation work in Alcator C-Mod and DIII-D had proven that a local transport model of heat transport could explain the temperature reversal. Nonetheless, it still remained unclear whether the propagation of the measured density puse could be explained by local physics as well. Simulation work of ASDEX Upgrade LBO-injected cold-pulse experiments [22] with the ASTRA transport code [88] coupled to STRAHL [28] for impurity transport calculations was used precisely to answer this question.

The carbon impurity ions present in the plasma following the LBO injection were included as kinetic species for the turbulent transport calculations with TGLF SAT-1, and both deuteron and carbon particle fluxes were used to self-consistently evolve the density profiles. Electron density was calculated by quasineutrality. Electron and ion temperatures, and deuterons and impurity densities were predicted all the way from the separatrix to the magnetic axis, and the arrival of carbon from the LBO was modeled as a local increase in carbon separatrix density. Simulations showed the exceptionally fast propagation of a density pulse from edge to core, quickly flattening the density gradients at mid-radius. Electron heat conductivity is also observed to be reduced as a consequence of the flattened density gradients in the TEM dominated plasmas, thus leading to the increase of the electron temperature peaking. Figure 8 shows the dynamics during these coupled simulations. The fast propagation of the density pulse was explained by the destabilization of an impurity density gradient driven mode as a consequence of the extremely large reversed impurity gradients that form locally after the LBO injection.

The work in ASDEX Upgrade was convincing proof that local transport physics not only explained the heat transport channel, but also the particle transport channel dynamics was fully explained by predictive transport simulations with the TGLF SAT-1 model.

3.6. Match with experimental phenomenology

As described in Section 2, a number of experiments have showed consistent trends with plasma parameters such as average density and plasma current. Increase of average density has universally led to a reduction of temperature reversal magnitude until their disappear-

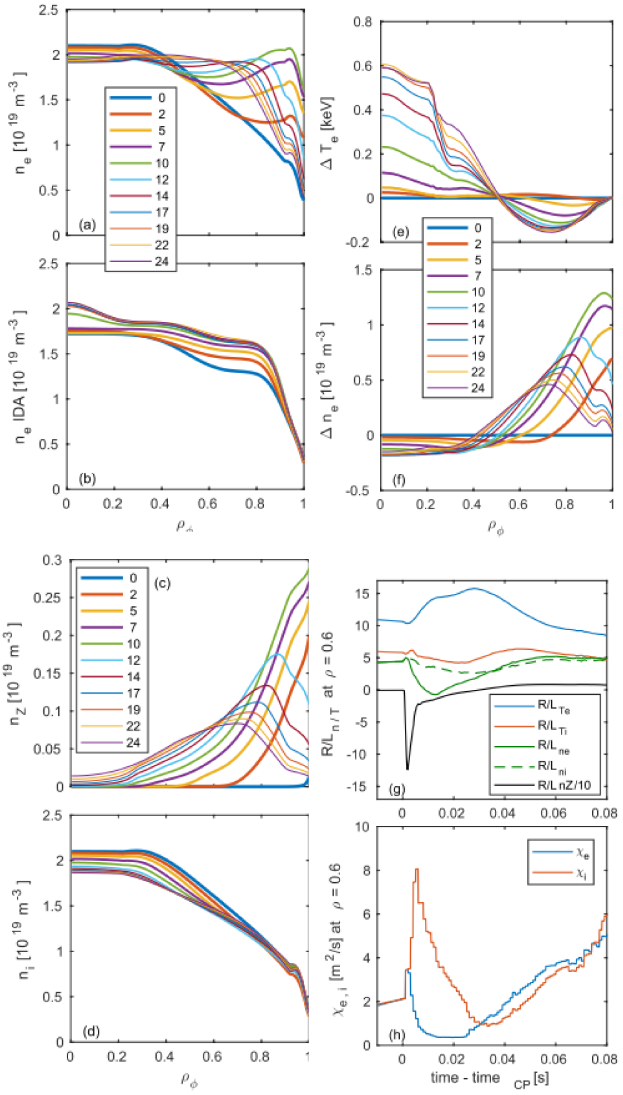

Figure 8. Profiles of (a) predicted electron density, (b) measured electron density, (c) predicted impurity density, (d) predicted deuterium density, during the cold pulse propagation. Variation of the (e) electron temperature and (f) electron density. (g) Gradients and (h) heat diffusivities evolution. Reproduced courtesy of IAEA. Figure from [22]. Copyright 2019 IAEA.

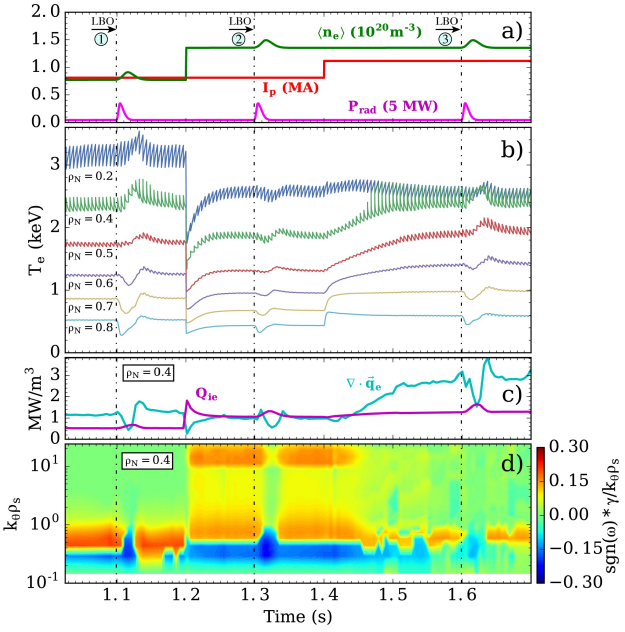

Figure 9. Simulation of combined density and plasma current scan with multiple cold-pulse injections in an Alcator C-Mod plasma. Quantities in plots: Plasma current, volume-averaged density and total radiated power; electron temperature traces; electron–ion collisional power and electron conducted power at $\rho_N = 0.4$; and low-k linear growth rates spectrum at $\rho_N = 0.4$, with sign representing direction of propagation (blue: ion diamagnetic direction; red: electron diamagnetic direction). Reproduced courtesy of IAEA. Figure from [21]. Copyright 2019 IAEA.

ance at high enough densities. Extensive simulation work via numerical experiments of Alcator C-Mod plasmas [21] has addressed this. Density scans at constant plasma current show the clear decrease of temperature reversal magnitude at higher plasma density (Figure 6). The increased collisionality led to de-trapping of electrons and the consequent reduction of TEM growth rates compared to ITG at long wavelengths. When the relative strength of estimated mixing length transport of TEM becomes lower than $\sim 0.7\times$ of ITG, temperature reversals disappeared. This is concomitant to the equalization of ion-electron collisional exchange and the conducted power density, which is consistent with the observation of stronger temperature reversals in plasmas with de-coupled ions and electrons, widely reported in the literature of cold-pulse experiments, and as discussed in Section 2.3. The loss of dominance of TEM in relation to ITG meant that the turbulence stabilization effect of the density pulse propagation is weak and not strong enough to compensate the increase of temperature gradients (destabilization of temperature gradient modes) at the pulse front, which causes the ubiquitous drop of temperature in the high density cases. Modeling of ASDEX Upgrade plasmas [22] with prescribed experimental electron density evolution also confirmed the absence of electron temperature reversals in conditions of intermediate to high density, as ITG turbulence becomes more dominant in the ion-scale range.

The effect of plasma current was also explored in scans of plasma current in numerical experiments of Alcator C-Mod plasmas [21]. At fixed density, the increase in plasma current led to increase electron heating, which further destabilized background TEM turbulence. Presence of more TEM turbulence throughout the plasma led to increased sensitivity to

the density pulse propagation, fully consistent with past work that showed that very high densities were required to make the temperature reversals disappear at high plasma current [59] (Figure 4). Simulation results of the effect of increasing plasma current are depicted in Figure 9. Furthermore, the electron temperature flex point also moved outwards with increasing plasma current, following the motion of rational surfaces observed in previous studies [37, 58].

Simulation work of ASDEX Upgrade [22] cold pulses also explored the predictive capabilities of TGLF on cold-pulse propagation in low-density NBI-heated plasmas. In the case studied, a reduction of ion-scale electron thermal diffusivity was observed following the density gradient flattening, but the destabilization of electron temperature gradient modes at short wavelengths prevented the appearance of the temperature reversal, consistent with experimental observations (see Section 2.3). It was determined that conditions with comparable values of T_e and T_i are affected by ETG transport and therefore cannot benefit from the reduction of density gradients that result from the density pulse propagation.

4. Discussion and Open Questions

The local paradigm presented in Section 3 has been extraordinarily successful in explaining cold-pulse phenomenology, while at the same time being truthful to the widely known and validated physics of drift-wave-type turbulent transport in the core of tokamak plasmas, and capable of reproducing the fast propagation of heat and particle transport events along with the slower dynamics which takes place on confinement time scales. The ubiquity of density perturbations in cold-pulse experiments suggests that the dynamics of particle transport and associated time variation of gradients are the key to the understanding of temperature reversals and cold-pulse propagation. This is often referred to as multi-channel transport effects, and the understanding of their importance is critical for the development of reliable models for particle, momentum and heat transport in tokamak plasmas. The literature of temperature reversal experiments is very extensive, and several other phenomenological observations still remain to be attempted from the perspective of local transport modeling. Nevertheless, there is no evidence that local transport physics as described in Refs. [19–22] is unable to explain the rest of experimental observations.

4.1. On the magnitude of the density perturbation

Only LBO-induced cold pulses were studied, as the localization of the particle sources facilitates the interpretation of the experimental results and the subsequent modeling. However, temperature reversals from cold pulses introduced via gas puffs, pellets and SMBI could be equally explained by the dynamics of the density profile and associated perturbations. As indicated in Section 3.3, density pulses are not exclusive from laser blow-off injections and therefore there is no basis as to assume that local transport physics does not explain the temperature reversals in such experiments.

Remarkably small density perturbations have been demonstrated [9, 20], in both experiment and simulation, to be enough to cause the reversal of the pulse in temperature, as shown in Figure 10. Significant changes to the density gradient are possible even with small changes in the absolute value of density (we hypothesize this as the reason why density pulses have long been disregarded in previous cold-pulse modeling studies). Transient changes in gradient scale lengths in situations where heat transport is stiff can cause the appearance of temperature reversals of significant magnitude and with fast time scales. Figure 11 shows that a 10 times smaller density perturbation can produce temperature increases of significant magnitude in Alcator C-Mod simulations.

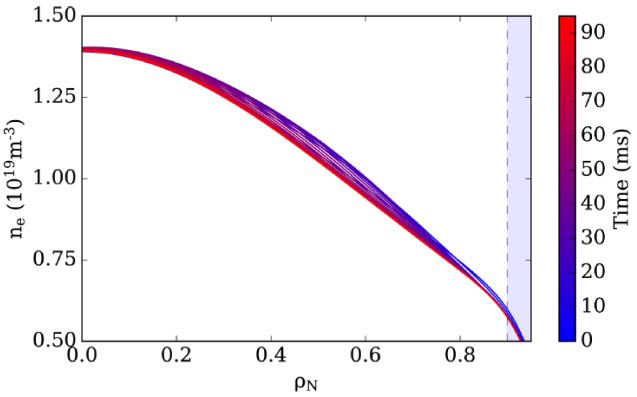

Figure 10. Range of variation of electron density profile used in simulations of DIII-D plasmas [20] during the propagation of cold-pulses that led to temperature reversals.

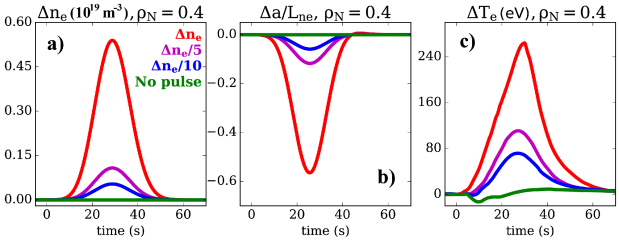

Figure 11. Relative evolution of the (a) density, (b) normalized density gradient scale length, and (c) electron temperature in the core ($\rho_N = 0.4$) of low-density simulation of Alcator C-Mod plasma, as a function of density pulse strength. Reproduced from [9]. Copyright 2019 MIT.

4.2. Ion temperature evolution

Cold-pulse experiments throughout the years have focused on the electron temperature perturbations, and the ion temperature evolution has only been reported in a few cases, owning to the difficulty to measure ion temperature with a time resolution enough to resolve the transient perturbation. Measurements of the ion temperature profile using crystal spectroscopy in Alcator C-Mod [30, 58] showed an increase in central ion temperature when reversals in the electron temperature occurred, although such evolution typically happened on a longer time scale. In the experiments reported, the edge ion temperature dropped promptly, and a moderate increase above pre-injection levels occurred later on. At high densities, similar to the electron temperature behavior, the increase in central ion temperature disappeared. Recent work in J-TEXT [63] further explored the ion temperature dynamics, and confirmed the Alcator C-Mod experimental results, with remarkable resemblance. The dynamics of the ion temperature during the density scan of Figure 6 is in qualitative agreement with the experimental observations, as depicted in Figure 12. Drops in edge ion temperature (followed by a later increase) are observed at low density, as well as an increase in core ion temperature. As the background density is increased, the core reversals also disappear.

However, the dynamics of the ion temperature during cold-pulse experiments is not as clear and robust as with the electron temperature. Experiments in Alcator C-Mod were reported where the edge ion temperature drop is not present [19]. Instead, an increase (on a longer time scale) of ion temperature was observed throughout the entire plasma. Furthermore, it has also been observed in Alcator C-Mod that the rise of central ion temperature may appear even when there is no corresponding electron temperature reversal [91].

Quantitative and qualitative match of the diverse ion temperature responses during cold-pulse experiments still remains an open question. However, given the experimental evidence provided and the modeling results, it can be determined that electron and ion temperature dynamics are not strongly coupled. The evolution of the ion temperature played a negligible role in driving the central electron temperature response in the simulations described here (as evidenced, for example, by the negligible effect of a/L_{T_i} on electron heat flux in the low-density TEM-dominated plasma in Figure 5c), and the fact that experimentally the ion temperature "reversal" is observed regardless of the behavior of the electron temperature channel suggests that the two are de-coupled. The full ion temperature dynamics and the interplay with the turbulence evolution that causes the electron temperature response still requires further investigation. Nonetheless, as indicated at the beginning of Section 4, there is no evidence that it could not be explained by local transport physics.

4.3. Effect of ECH deposition location

Experiments in RTP [38] showed that the ECH deposition location has one of the strongest effects on the magnitude of the temperature reversals, reaching values of up to 80% the background temperature when ECH is applied nearby the $q = 1$ flux surface. While this trend remains unexplained at the time of writing this review article, it could still be reconciled within the local transport physics explanation. As ECH heats up the approximate region of the temperature flex point, stronger TEM turbulence activity is expected at low collisionality. This means that electron heat transport may become more sensitive to density gradients, thus driving a stronger temperature reversal for the same density pulse perturbation. This is similar to the observation that at higher plasma current stronger temperature reversal responses at the same average density, as discussed in Section 3.6. The link to the location of rational surfaces could be due to the changes in what regions of the plasma are dominated by one or other type of turbulent modes, as discussed in Ref. [21].

Nonetheless, these past experiments should be reconsidered in detail in light of the local modeling results presented in this review article. Modeling should be performed in the specific conditions of those experiments before one can conclude that the local paradigm can or cannot explain also those observations.

5. Final remarks

This review article has covered the experimental and simulation evidence that cold-pulse propagation in the core of tokamak plasmas can be fully explained by local physics, including the seemingly "nonlocal" temperature reversal and speed of propagation. This experimental observation had been puzzling plasma physicists for over two decades, but thanks to experimental and computational work in Alcator C-Mod, DIII-D and ASDEX Upgrade, there is convincing evidence that the widely-validated theory of drift-wave turbulent transport can indeed fully explain the experimental behavior in such perturbative experiments while, at the same time, capture the steady-state confinement features. In fact, local or flux-tube transport models are sufficient to cause the fast reversal of core electron temperature. The variation of density gradients during the perturbative transport response has been demonstrated to both cause the temperature reversal at low collisionality [19] and also be in alignment with the local paradigm [22].

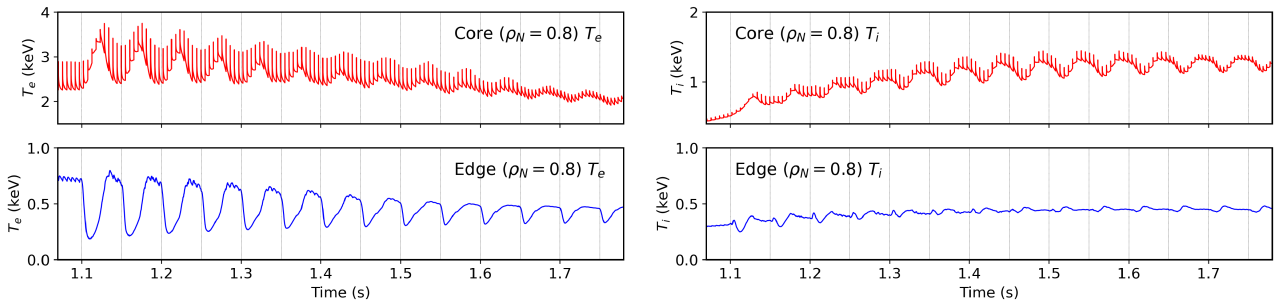

Figure 12. Dynamics of the core and edge electron and ion temperatures during the density scan of Figure 4.

While this work provides further evidence that local transport modeling within the framework of the conventional quasilinear turbulent transport description and the usual diffusive heat transport equation has been successful in explaining the propagation of fast LBO-induced pulses, this study has not covered other perturbative transport phenomena (such as the propagation of heat pulses using modulation of ECH heating power), explored the validity of standard local transport theory in stellarators, or claimed perfect and conclusive understanding of all transport problems. Nonetheless, the cold-pulse propagation in the core of tokamaks seems to be fully dominated by local turbulent transport effects. Truly nonlocal mechanisms were not needed to reconcile experiment and simulation, and while they may be important to study certain transport phenomena, they certainly were not the dominant effect in the cold-pulse experiments in tokamaks.

As it has been shown in this work, the fact that the plasma is able to react on time scales that are extremely fast (much faster than the energy confinement time or time scales derived from average heat diffusivities) *cannot* be considered evidence that nonlocal effects have to be present. This work has demonstrated that plasma dynamics can produce very fast responses (which at first sight may seem nonlocal) that are still fully compatible with conventional transport physics, as described by second-order diffusive equations, and simultaneously also predict slower dynamics, on time scales which are comparable to experimentally-relevant confinement times. The compatibility of the conventional local transport paradigm with very fast phenomena is allowed by the rich nonlinearity present in the parametric dependencies of the transport coefficients. Such dependencies directly connect different plasma parameters, leading to interesting multichannel transport effects that must be accounted for in the predictions of transport in tokamak plasmas.

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