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Electron Temperature Fluctuation Measurements and Transport Model Validation at Alcator C-Mod

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Section 1: Executive Summary

The tokamak is a type of toroidal device used to confine a fusion plasma using large magnetic fields. Tokamaks and stellarators the leading devices for confining plasmas for fusion, and the capability to predict performance in these magnetically confined plasmas is essential for developing a sustainable fusion energy source. The magnetic configuration of tokamaks and stellarators does not exist in Nature, yet, the fundamental processes governing transport in fusion plasmas are universal – turbulence and instabilities, driven by inhomogeneity and asymmetry in the plasma, conspire to transport heat and particles across magnetic field lines and can play critical roles in impurity confinement and generation of intrinsic rotation. Turbulence exists in all plasmas, and in neutral fluids as well. The study of turbulence is essential to developing a fundamental understanding of the nature of the fourth state of matter, plasmas.

Experimental studies of turbulence in tokamaks date back to early scattering observations from the late 1970s. Since that time, great advances in turbulence diagnostics have been made, all of which have significantly enhanced our knowledge and understanding of turbulence in tokamaks. Through comparisons with advanced gyrokinetic theory and turbulent-transport models a great deal of evidence exists to implicate turbulent-driven transport as an important mechanism determining transport in all channels: heat, particle and momentum. However, prediction and control of turbulent-driven transport remains elusive. Key to development of predictive transport models for magnetically confined fusion plasmas is validation of the nonlinear gyrokinetic transport model, which describes transport due to turbulence. Validation of gyrokinetic codes must include detailed and quantitative comparisons with measured turbulence characteristics, in addition to comparisons with inferred transport levels and equilibrium profiles. For this reason, advanced plasma diagnostics for studying core turbulence are needed in order to assess the accuracy of gyrokinetic models for turbulent-driven particle, heat and momentum transport.

New core turbulence diagnostics at the world-class tokamaks Alcator C-Mod at MIT and ASDEX Upgrade at the Max Planck Institute for Plasma Physics have been designed, developed, and operated over the course of this project. These new instruments are capable of measuring electron temperature fluctuations and the phase angle between density and temperature fluctuations locally and quantitatively. These new data sets from Alcator C-Mod and ASDEX Upgrade are being used to fill key gaps in our understanding of turbulent transport in tokamaks. In particular, this project has results in new results on the topics of the Transport Shortfall, the role of ETG turbulence in tokamak plasmas, profile stiffness, the LOC/SOC transition, and intrinsic rotation reversals. These data are used in a rigorous process of “Transport model validation”, and this group is a world-leader on using turbulence models to design new hardware and new experiments at tokamaks.

A correlation electron cyclotron emission (CECE) diagnostic is an instrument used to measure micro-scale fluctuations (mm-scale, compared to the machine size of meters) of electron temperature in magnetically confined fusion plasmas, such as those in tokamaks and stellarators. These micro-scale fluctuations are associated with drift-wave type turbulence, which leads to enhanced cooling and mixing of particles in fusion plasmas and limits achieving the required temperatures and densities for self-sustained fusion reactions. A CECE system can also be coupled with a reflectometer system that measured micro-scale

density fluctuations, and from these simultaneous measurements, one can extract the phase between the density (n) and temperature (T) fluctuations, creating an nT phase diagnostic. Measurements of the fluctuations and the phase angle between them are extremely useful for testing and validating predictive models for the transport of heat and particles in fusion plasmas due to turbulence. Once validated, the models are used to predict performance in ITER and other burning plasmas, such as the MIT ARC design.

Most recently, data from the newly developed, so-called “CECE diagnostic” [Cima 1995, White 2008] and “ nT phase angle measurements” [Haese 1999, White 2010] will be combined with data from density fluctuation diagnostics at ASDEX Upgrade to support a long-term program of physics research in turbulence and transport that will allow for more stringent testing and validation of gyrokinetic turbulent-transport codes. This work directly impacts the development of predictive transport models in the U.S. FES program, such as TGLF, developed by General Atomics, which are used to predict performance in ITER and other burning plasma devices as part of advancing the development of fusion energy sciences.

Section 2: Summary of Project Activities

In Section II of this final report, we summarize our project activities for the entire period of funding. We have included in each scientific area a statement of our original hypotheses, the approaches we used to test them, and our findings. Only very brief accounts of the analyses and details are provided in this section, since all of the results described (with the exception of the figures shown in Section 2.3) have been published. We direct the reader to Section 3 of this report for in-depth presentation of facts, figures, analyses and assumptions that supported the STI created during this project. Section 3 includes lists of all the peer-reviewed journal articles, and a selection of conference presentations, which can be accessed by the public.

2.1 Electron temperature fluctuations at Alcator C-Mod: Design and Development of a new Correlation ECE radiometer

As described in the Executive Summary, A correlation electron cyclotron emission (CECE) diagnostic is an instrument used to measure micro-scale fluctuations (mm-scale, compared to the machine size of meters) of electron temperature in magnetically confined fusion plasmas, such as those in tokamaks and stellarators. These micro-scale fluctuations are associated with drift-wave type turbulence, which leads to enhanced cooling and mixing of particles in fusion plasmas and limits achieving the required temperatures and densities for self-sustained fusion reactions. For details of how such measurements are made in tokamaks, we refer you to [White 2008] and Freethy 2016].

When a CECE system was first implemented at C-Mod in 2004, the team did not find any temperature fluctuations in C-Mod [Watts 2007], which was a strikingly different result from those seen previously in TEXT [Cima 1995] and W7X [Sattler 1994] and later observed in DIII-D [White 2008].

This left intriguing open questions for me when I began working at MIT and collaborating with the C-Mod team: Why were the results from DIII-D and C-Mod so different? Were temperature fluctuations (T_e fluctuations) fundamentally different in C-Mod? And if so, would electron heat transport in C-Mod plasmas substantially different from other tokamaks? Was the turbulence suppressed due to higher collisionality? Was the turbulence harder to detect due to finer scale of fluctuations as expected at high magnetic field?

A working hypothesis was developed: T_e fluctuations in C-Mod should be similar in nature to those observed in other tokamaks and the dominant reason the fluctuations were not detected in C-Mod in past attempts is due to the design of the radiometer-based instrument. I believed that the T_e fluctuations in C-Mod should be typical drift-wave type fluctuations and as such, would be described by nonlinear gyrokinetic turbulence models. This would mean that the observable T_e fluctuation characteristics (frequency spectrum and fluctuation amplitude) should be correctly predicted by gyrokinetic simulations, and that a new radiometer based instrument (a Correlation ECE (CECE) diagnostic [White 2008]) could be built with new specification, and would allow for measurement of T_e fluctuations in C-Mod.

A novel “predict-first” approach based on nonlinear gyrokinetic simulations was used to test the hypothesis. Using a priori and ab initio gyrokinetic simulations, simulations of low confinement L-mode plasmas on C-Mod were carried out. The results of these simulations is recorded [White 2011]. These simulations were used to design a new radiometer based instrument to measure temperature fluctuations on C-Mod. The subsequent design of the new instrument is documented in two articles [Sung 2012] and Howard 2014]. The new CECE diagnostic was constructed using the predictive GYRO simulations to constrain the design parameters, which had never been done before.

The findings confirmed the hypothesis. The temperature fluctuations were measured in Alcator C-Mod and were found to have characteristics consistent with the predictions. Major experimental observations of electron temperature fluctuations as measured in C-Mod were published as follows:

- LOC/SOC plasmas – T_e fluctuations in the core are reduced across the confinement transition from LOC to SOC [Sung 2013]
- L-I mode – T_e fluctuations in the core are reduced across the confinement transition from L-mode to I-mode [White 2014]
- Temperature fluctuations are typically very low in H-mode below the sensitivity limit of diagnostic [Sung PhD 2015] but in some low current H-modes, the fluctuations can be detected in the outer core region.

2.2 Transport model validation at Alcator C-Mod

The new CECE diagnostic described in the previous section was used in a variety of experiments and the data was used as part of validation efforts at C-Mod. Validation of nonlinear gyrokinetic transport models requires careful comparison between experiments and simulations, with rigorous testing of sensitivities to experimental uncertainties. This

section will describe topic-by-topic several research projects on transport model validation at C-Mod carried out as part of this grant, as enabled by the CECE measurements and the associated validation “infrastructure” (our research team and our suite of post-processing codes and tools) built up around the CECE system.

2.2.1 Transport Shortfall

A so-called “transport shortfall” was documented in certain DIII-D [White 2008, Holland 2009] L-mode plasmas with GYRO. The shortfall at DIII-D manifests as an underprediction of the ion and electron heat fluxes and the temperature and density fluctuations in the outer core of the plasma ($r/a > 0.7$). In contrast, the same simulations at DIII-D show that the ion-scale simulations can match all measurements simultaneously (Q_e , Q_i , T_e tilde and n_e tilde).

There were several open questions surrounding the shortfall when I arrived at MIT in 2010. First, was the shortfall due to missing physics in the model used by GYRO, and therefore was it a universal effect in the edge of all tokamak plasmas? Or was it due to a peculiarity of this type of L-mode plasma at DIII-D?

The hypothesis we set out to investigate was as follows: the shortfall is not due to missing physics in GYRO and should not be universal. If the same type of GYRO model were to be used to simulate C-Mod plasmas, the shortfall should not be observed.

To approach this open question, we carefully designed validation experiments to test this hypothesis and nonlinear GYRO simulations were run on these plasmas to search for evidence of the short fall. The simulations and results are documented in [Howard 2013].

We found that the shortfall is not observed in C-Mod plasmas [Howard 2013] using the identical GYRO model as was used at DIII-D [Holland 2009]. The shortfall at DIII-D is therefore not due to any missing physics in the GYRO model and is not universal. It must be a peculiarity of that one type of L-mode at DIII-D. This experimental result from C-Mod is consistent with other theoretical results, where other gyrokinetic codes that employ different models (e.g. GENE uses different model for ExB shear and collisions) do not see the shortfall in the DIII-D L-mode of interest [Goerler 2015].

2.2.2 The role of electron scale turbulence (ETG) in determining heat fluxes in Alcator C-Mod L-mode plasmas

As a result of the shortfall investigations, we found that ion-scale GYRO simulations could not match both the ion and electron heat fluxes in certain L-mode plasmas at C-Mod, but could match them in other L-mode plasmas [Howard 2013].

This led to several open questions of interest: in the cases where the ion-scale simulations at C-Mod underpredicted the electron heat flux, was the underprediction due to missing the electron scale physics? Since the simulations used in [Howard 2013] did not include ETG and only included ITG and TEM, would inclusion of the ETG physics resolve the Q_e underprediction? Is ETG an important player in simple L-mode plasmas? Much

past work suggested the ETG was usually only important in the core of H-mode plasmas and in the plasma pedestal, when ions scale turbulence is suppressed by ExB shear.

Our working hypothesis was that The ETG is important in certain C-Mod L-mode plasmas and should be included in “multi-scale” simulations.

To test this hypothesis, Dr. Nathan Howard began a long project of running the first ever realistic mass multi-scale (coupled ITG TEM ETG) nonlinear gyrokinetic simulations with GYRO. He led this work and documented his findings in a series of articles [Howard 2014, Howard 2016]

The findings were consistent with the hypothesis. Multiscale simulations are needed to explain the electron heat transport in certain C-Mod L-mode plasmas [Howard 2014, Howard 2016] Moreover, the effects of cross-scale coupling are also important in certain H-mode plasmas, such as ELMy H-mode ITER targets. The culmination of Dr. Howard’s efforts and these validation experiments at C-Mod was the use of the new multiscale GYRO results to develop the new TGLF SAT1 model [Staebler 2017]. The reduced TGLF SAT1 model can be used in lieu of expensive nonlinear multi-scale simulations to explore the impact of cross-scale coupling on transport predictions for ITER and other burning plasma devices.

2.2.3 Development of a new measurement technique for perturbative heat diffusivity in tokamaks

In addition to the CECE measurements at Alcator C-Mod, our team was also collaborating with the DIII-D group on comparing measurements of “profile stiffness” to transport models [Smith 2015]. At DIII-D, Electron Cyclotron Heating (ECH) can be used to create heat pulses, and by measuring the propagation of the heat pulses, one can infer the perturbative thermal diffusivity, in contrast to the steady state thermal diffusivity. The perturbative thermal diffusivity can be compared to the model flux gradient curve (heat flux versus driving gradient) constructed from a series of simulations (e.g. from GYRO or TGLF [Smith 2015].

It was an open question whether the ion-scale or multi-scale gyrokinetic transport model described in section 2.2.2 would be able to match the experimental stiffness or not, and since we had multi-scale simulations for C-Mod L-mode plasmas, but no measure of the perturbative thermal diffusivity, we set out to find a novel method of extracting this data from existing measurements at C-Mod.

Since ECH is unavailable on C-Mod due to the very high magnetic field (5.4T) at standard operation, we tried to develop a passive technique for extracting the perturbative thermal diffusivity using heat pulses generated at sawtooth crashes. Our initial hypothesis was that the full sawtooth heat pulse could be used [White 2015], but it was later shown that this heat pulse involves a “ballistic” plasma response in C-Mod L-modes, so we abandoned this method [Creely 2016]. However, student Alex Creely discovered that many L-mode plasmas at C-Mod contain partial sawtooth crashes, and that the heat pulses generated by these partial crashes do not exhibit ballistic behavior, but rather appear to be governed by diffusive processes. Using the partial sawteeth, it became possible to extract

the perturbative thermal diffusivity (a measure of profile stiffness) in a variety of L-mode and I-mode plasmas at C-Mod [Creely 2016]

2.2.4 Using new perturbative heat diffusivity measurements to probe the role of electron scale turbulence in determining heat fluxes in high-performance I-mode plasmas at Alcator C-Mod

Unlike the L-mode plasmas studied by Howard for his multi-scale simulations [Howard 2016], ion scale simulations with GYRO tended to agree well with both ion and electron heat fluxes in I-mode plasmas [White 2015].

This raised a variety of open questions: knowing what we discovered from Howard's work, how valid are the ion scale models for I-mode? What other measurements can be used to constrain them? That is, in addition to the good agreement with the heat fluxes, would the ion-scale simulations also be in agreement with the measured CECE Te fluctuations in I-mode? Would the ion-scale simulations be in agreement with the robust trend that I-mode plasmas are more stiff than L-mode plasmas [Creely 2016]?

Our working hypothesis was that the ETG is important in I-mode plasmas and should be included in "multi-scale" simulations, and we speculated that this will manifest as disagreements between the experimental fluctuation levels and stiffness, even if the heat fluxes agreed.

To test this hypothesis, the perturbative thermal diffusivity [Creely 2015] was measured in a well-diagnosed plasma discharge that underwent an L to I transition. The plasma of interest had CECE measurements available, so that the nonlinear simulations could be constrained using TRANSP (power balance) ion and electron heat fluxes and CECE Te fluctuation measurements and perturbative diffusivity (stiffness) measurements.

We found that the ion-scale simulations did in fact underpredict the stiffness, even in cases where the equilibrium heat flu could nearly be matched. However, the simulations also underestimated the fluctuation levels. And interestingly, when we ran TGLF-SAT1 to investigate the role of multi-scale effects, we found that SAT1 could not explain the disagreement in the heat fluxes, stiffness, and fluctuation levels self-consistently. This work was presented by Alex Creely at his invited APS-DPP talk in 2016, and published in 2017 [Creely 2017]. It is also interesting to note that S. Smith presented a similar conclusion for DIII-D plasmas at TTF in 2016, namely that TGLF-SAT1 could not self-consistently match heat fluxes and perturbative thermal diffusivities in ECH heat pulse experiments [Smith 2016].

The overall result of this study is many more open questions. We think that there may be an overestimate of the electron profile stiffness predicted by SAT1 (and we would like to test this as part of cross-machine validation, see Section 2.3. In addition, we hypothesize that the role of the ETG and cross-scale coupling, multi-scale effects, are more pronounced in C-Mod [Creely 2017] and DIII-D cases [Smith 2016] than in many ASDEX Upgrade cases already studied [Told 2013], and that differences between how well ion-scale gyrokinetics can model the measured CECE Te fluctuations will help elucidate what is

missing from SAT1 that is needed to find a self-consistent solution for C-Mod and other plasmas of interest. This will be the topic of future work.

2.2.5 Change of ITG/TEM turbulence across the LOC/SOC transition

The LOC SOC transition is seen on many tokamaks, and is believed to be a rather universal transport phenomena. Despite a great deal of study for many years, what causes the saturation of the energy confinement remains an open question. At C-Mod, it has been shown that other effects appear to be concomitant with the transition in many regions of parameter space [Sung 2013 and references therein]. Widely speculated in community that ITG TEM changes in mode dominance can play a role [Sung 2013 and references therein].

Our working hypothesis is that the LOC SOC transition is caused by a variety of nonlinear turbulent and other effects, but that a change from dominant TEM type turbulence at low collisionality in the LOC plasma to dominant ITG type turbulence at higher collisionality in the SOC plasma may play a key role. This would be consistent with the observed reduction in T_e fluctuations in SOC [Sung 2013] and would be consistent with the changes in intrinsic rotation direction as theory suggests the Reynolds stress turbulent driven source term can vary direction based on the sign of the real frequency of the turbulence (e.g. difference between ion modes and electron modes) and therefore the ITG/TEM paradigm presents a unifying model for the LOC/SOC [Rice 2013]

Our approach at C-Mod has been to conduct carefully designed validation experiments were designed to test this hypothesis and linear and nonlinear GYRO simulations were run on these plasmas to search for evidence of the ITG / TEM transition. The measurements and simulations are documented in [Sung 2013, Sung 2016, Kwak MS 2015, and Sung PhD 2015].

Our current findings from C-Mod contradict the hypothesis at this time. In most LOC/SOC plasmas at C-Mod we have studied, the core plasma tends to be dominated by ITG-type turbulence, and there is little to no evidence suggesting that a change of turbulence type from TEM to ITG accompanies the confinement transition [Sung 2016, Kwak 2015]. This is a very active area of investigation, and our group is now applying new reduced models such as TGLF-SAT1 to explore the possibility that electron scale turbulence (ETG) plays a role in the LOC/SOC transition as well. We hope to study these effects more at DIII-D and at ASDEX Upgrade in the future, as part of cross-machine validation efforts (See Section 2.3).

2.2.6 Change of low-k ITG/TEM turbulence as a cause of intrinsic rotation reversals in tokamaks

Closely related to the LOC SOC effort just described, we also conducted experiments to use ICRF heated plasmas to probe the hypothesis that a change in turbulence was responsible for changes in intrinsic rotation, momentum generation and transport in tokamaks.

It is an open question as to what causes the intrinsic rotation reversals observed in tokamaks [Sung 2013]. It has been widely speculated in community that ITG

TEM changes in mode dominance can play a role, c.f. [Sung 2013 and references therein].

We hypothesize that a change in dominant mode structure from ITG to TEM type is consistent with the changes in intrinsic rotation direction as theory suggests the Reynolds stress turbulent driven source term can vary direction based on the sign of the real frequency of the turbulence (e.g. difference between ion modes and electron modes) and therefore the ITG/TEM paradigm presents a unifying model for the LOC/SOC [Sung 2013 and references therein].

At C-Mod, carefully designed validation experiments were designed to test this hypothesis and linear and nonlinear GYRO simulations were run on these plasmas to search for evidence of the ITG / TEM transition. The measurements and simulations are documented in [White 2013].

The experiments and modeling appear to contradict the hypothesis. The data revealed that the intrinsic rotation can reverse direction in ICRF heated plasmas even when there is not change from changes from ITG to TEM (i.e. the plasma stays ITG dominated). Interestingly, there are reductions in low-k Te fluctuations measured with CECE that do correlate with the rotation reversals, but the low-k density fluctuations measured with the reflectometer in the core plasma do not change. The experiments also revealed that an imposed change in turbulence type (e.g. controlled change from ITG to TEM dominance) could occur in the plasma without any change in the rotation state (without a rotation reversal.) [White 2013].

This experiment was important because it was the first strong evidence from controlled experiments showing that changes in turbulence, changes in ion and electron heat flux, could all be decorrelated from momentum transport under certain conditions. This is intriguing because much work up until this point postulated that ion heat transport was strongly connected to the momentum transport, and this remains a prevailing theory that is consistent with some experimental observations [Grierson 2017]. This latter theory would indicate that changes in low-k turbulence, particularly ITG, would be related to the rotation reversals. The C-Mod data set appears to contradict this postulation and would appear to suggest that cases when ITG is found to be a driver for rotation reversals [Grierson 2017] are not universal across all regions of tokamak parameter space. More work is being done to analyze and model rotation reversal data sets from C-Mod using turbulent transport models such as TGLF and GYRO. This is an area of research that is ripe for cross-machine validation.

2.3 Cross-Machine Transport Model Validation

One of the exciting possibilities enabled by a new CECE and nT phase diagnostic at ASDEX Upgrade (AUG) is cross-machine comparisons. With a wealth of CECE data from the DIII-D and C-Mod tokamaks, and the availability of nT phase measurements at DIII-D, we are anticipating that over the next 5 to 10 years far more stringent tests and validation of transport models will be possible using the same types of fluctuation data from multiple machines. With this motivation, we embarked on the

development of these new fluctuation measurements with CECE and nT phase at AUG, as summarized in this section. Many of the results shown here are not yet published in peer-reviewed journals, but have been presented at several conferences since 2015 (see Section 4).

2.3.1 Development of new CECE and nT phase diagnostics at ASDEX Upgrade

In the past, A CECE diagnostic was designed and built for C-Mod using nonlinear gyrokinetic simulations to ‘predict first’ how the system should be built [White 2011]. In addition, an experiment at DIII-D to measure the nT phase angle was designed using nonlinear gyrokinetic simulations to ‘predict first’ how the measured phase angle should change with application of ECH to a NBI heated L-mode plasma [White 2010].

We planned to build a new CECE system at AUG, and then, since a CECE system can also be coupled with a reflectometer system that measured micro-scale density fluctuations, and from these simultaneous measurements, one can extract the phase between the density (n) and temperature (T) fluctuations, creating an nT phase diagnostic.

Open question – Can CECE and nT phase be successfully deployed on ASDEX Upgrade? Will the temperature fluctuations be measurable on ASDEX Upgrade with the existing reflectometer optics [Happel 2013]. If the temperature fluctuations cannot be detected with the existing optics, then it would not be possible to quickly implement CECE and nT phase at AUG, because one would need several years to obtain port space for new optics etc.

Given past validation work with GENE nonlinear simulations of AUG plasmas [Told 2013], we hypothesized that the long wavelength turbulence in AUG can be accurately predicted using standard ion-scale nonlinear gyrokinetic simulations. We can use these existing simulations to now ‘predict first’ what the expected temperature fluctuation levels are in AUG, to help us determine whether or not we can install a new CECE system to share the existing optics with the reflectometer at AUG (to enable new Te-fluctuation measurements and nT phase measurements)

Beginning in 2012, Prof. Anne White (MIT) and Garrard Conway (IPP) began informal discussions, to explore possibilities for developing a new correlation electron cyclotron emission (CECE) diagnostic at the tokamak ASDEX Upgrade (AUG), located in Garching, Germany, at the German national laboratory for plasma physics (Max Planck Institute fuer Plasma Physik (IPP)). IPP is more or less the German equivalent of the US national laboratory for plasma physics, Princeton Plasma Physics Laboratory (PPPL) in Princeton, NJ, USA.

In May 2013, Prof. White gave a remote talk on CECE possibilities at AUG and MIT graduate student Choongki Sung visited IPP to discuss CECE measurements from C-Mod and to discuss how that CECE hardware could be adapted for use at AUG. GENE predictions were carried out using results from [Told 2013], and these predictions were used to identify that the existing reflectometer optics [Happel 2013] at AUG were viable for CECE. Based on these predictions, plans for collaboration are firmed up, and back at MIT, the hardware for what will become the first 4 channel CECE system at AUG is developed and tested (by C. Sung, MIT PhD student, and D. Kwak, MIT MS student, and White). Prof. White visits IPP in July 2013 to finalize plans for loan of CECE hardware

and to identify on-site support needed with Conway.

In 2014, MIT and IPP finalized plans for a subcontract to facilitate collaboration over the next 3 years, funded by US DOE Early Career Award (White, Principal Investigator). A hardware loan was finalized around the same time. In February 2014, the first 4-channel CECE system was shipped from MIT and arrived at AUG. At MIT, development of new hardware, new purchases of digitizers, filters, etc. for future AUG CECE systems continues (C. Sung, D. Kwak, White). At AUG, the new system is online and acquiring data by Summer 2014 (Conway). An active search for Postdoc, to work on-site at AUG and be paid by the subcontract is carried out in Summer and Fall 2014. In Fall 2014, Alex Creely, a new MIT PhD student joins the collaboration, working on CECE at C-Mod in parallel with AUG. Visits from MIT to IPP continue (White).

In February 2015, Dr. Simon Freethy joins team as off-site postdoc, paid through the new subcontract. He is also an MIT affiliate. In Spring/Summer 2015 new CECE and nT phase hardware is shipped to IPP from MIT, including a new digitizer, a new 4 channel receiver for the nT phase diagnostic, with two tunable filters, new hardware to increase number of channels in first CECE system, and a new RF section (LO, mixer) for nT phase diagnostic. During 2015, Simon used CECE to obtain electron temperature fluctuation δT_e profiles in L-mode edge (Simon Freethy & MIT PhD student Alex Creely).

Collaboration with W7X discussed (Freethy, Weir), where IPP is fielding another CECE system at the stellarator at the German national lab in Greifswald, Germany. Freethy and White write a MISTI Seed Fund proposal to support UROP travel and a summer internship for research in Germany (it is not funded). Extensive GENE simulations are performed to compare nonlinear GK simulations to CECE measurements at AUG (Goerler). New CECE and nT phase hardware for AUG is developed at MIT (Creely with engineers David Terry and Willy Burke).

2.3.2 First CECE and nT phase results from ASDEX Upgrade

In the 2016 AUG run campaign, CECE is used to gather excellent data set of temperature fluctuations in L-mode plasmas (He and D). Measurements of broadband, turbulent temperature fluctuations that were made in two Helium plasmas with magnetic field of 2.5 T, plasma current of 800 kA, core line-averaged density of $2.1 \times 10^{19} \text{ m}^{-3}$ and $4.6 \times 10^{19} \text{ m}^{-3}$, respectively. The plasmas had 0.52 MW of Ohmic heating and 0.67 MW of Electron Cyclotron Resonance Heating (ECRH). This is the first time that core electron temperature fluctuations have been measured in Helium tokamak plasma discharges, and these results were presented by S. Freethy at the European Physical Society (EPS) annual meeting in 2016. Comparisons with measurements typically made in Deuterium are important. In the initial phases of ITER operation, ITER will run Helium plasmas, with a mix of Hydrogen and/or Deuterium. Understanding turbulent transport and predicting turbulent transport in all phases of ITER operations is of great interest.

Figure 1 shows three coherence spectra in panel (a) from three different radial locations in the He L-mode plasma at AUG. Integrating the spectra gives the fluctuation levels, and a particle profile of the temperature fluctuation level is shown in panel (b). The statistical noise limit (when the CECE diagnostic is unable to distinguish the real fluctuations from the noise) is shown as the shaded grey region. More details on these measurements and hardware development are found in Freethy's RSI article, published in 2016, and in his corresponding presentation at the High Temperature Plasma Diagnostics (HTPD) conference in 2016, which documents the CECE and nT phase diagnostic development at AUG.

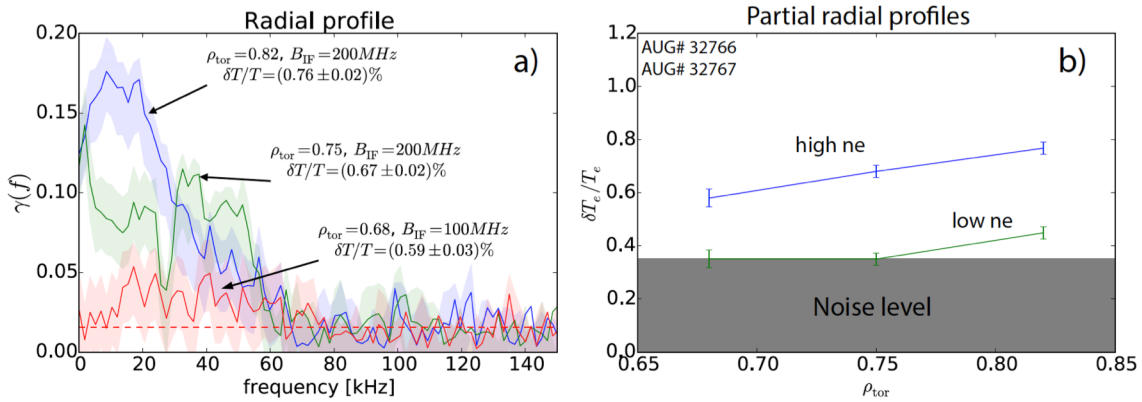


Figure 1: a) Coherence spectra measured with the CECE diagnostic at AUG in a Helium L-mode plasma (ECRH) at three different radial positions. The area under the curves corresponds to the relative amplitude of the turbulent temperature fluctuations. b) Partial radial profiles of the fluctuation level in two L-mode plasmas, the fluctuation level decreases as density increases. The higher density plasma has nearly a factor of 2 smaller fluctuation amplitude. These results were presented at the EPS 2016 conference by Simon Freethy and are currently being compared with nonlinear GENE simulations as part of validation efforts.

Because the CECE diagnostic at AUG has been installed in a highly modular fashion, similar to what was used at C-Mod [Sung RSI 2012, Howard RSI 2013, Freethy RSI 2016]], we are able to couple the ECE receiver with a suite of existing reflectometers at AUG. This allows for the development of an nT phase diagnostic. A prototype nT phase diagnostic was installed on AUG in 2016, and first light is observed. Figure 2 shows the nT phase measured in the edge region of the tokamak (near $r/a \sim 0.9$, optical depth = 2) in an L-mode plasma. In the upcoming 2017 campaign, we plan to use upgraded CECE receiver hardware to improve upon these preliminary nT phase measurements, working towards optimizing them for validation studies (See Section 2.4.3). Modeling of the initial nT measurements is also underway, using full-wave codes and reduced models for the reflectometer plasma response.

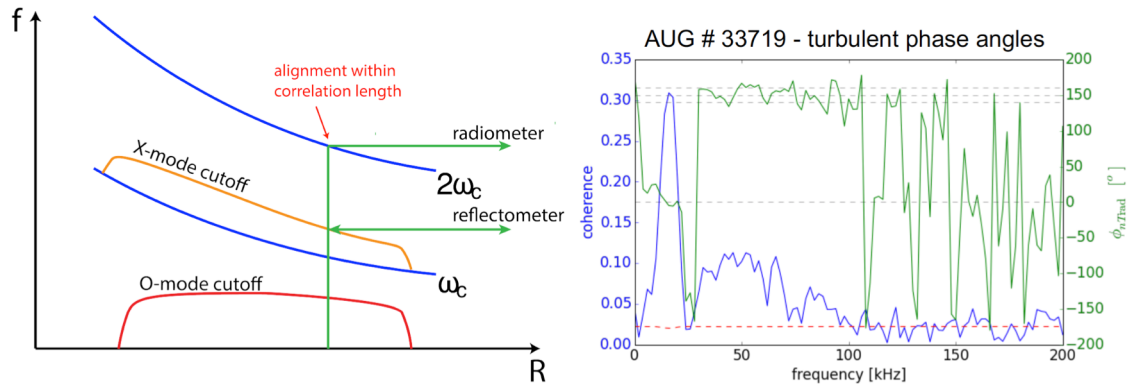


Figure 2. Left panel illustrates the principle of an nT phase diagnostic: overlapping the spatial mapping of the ECE frequency range (for the CECE radiometer) with the spatial mapping of the cut-off frequency range used for a reflectometer measurement. The Right panel shows the phase angle between density and electron temperature fluctuations, the nT phase, measured at AUG in the edge plasma ($r/a \sim 0.9$) with a prototype nT phase diagnostic fielded by MIT in the 2015-2016 campaign. The initial measurement suggests that the density and temperature fluctuations are out of phase, but more work is needed to fully model these results. These results were presented by Freethy at the APS-DPP meeting in 2016, and the US-EU TTF meeting in 2017.

2.3.3 Synthetic Diagnostic Development and Comparison with the Nonlinear Gyrokinetic code, GENE

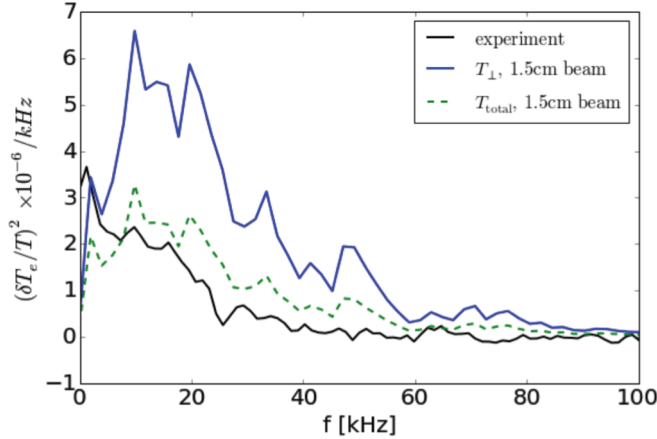


Figure 3. Comparison between the experimental CECE turbulent electron temperature fluctuation spectrum in a Deuterium L-mode plasma and the output of the GENE code with the new synthetic diagnostic applied. The GENE code allows the user to separate the temperature fluctuations into the perpendicular components and contrast this with the total fluctuations (perpendicular plus parallel), allowing for more detailed comparisons of the theoretical fluctuation levels and the experiment that is possible with other codes (e.g. GYRO). This result was presented by Freethy at US-EU TTF meeting in 2017.

This CECE data set from Helium and Deuterium L-mode plasmas at AUG is now being used for a validation effort using the GENE code, in collaboration with Dr. Tobias Goerler at IPP. Dr. Goerler is an expert in transport model validation, and developed the first CECE synthetic diagnostic for the GENE code. In order to develop a new synthetic diagnostic to mimic the measurements as they were made at AUG in the 2015-2016 run campaign, we have been making a series of laboratory measurements of the transmission line properties and the antenna pattern. These measurements are made in collaboration with two university groups, one from Stuttgart and one from the Technische Universitaet Muenchen (TUM). Using the new measurements of the CECE spot size, a new CECE synthetic diagnostic for AUG is under development. Preliminary comparisons with the GENE code

show are promising, and a variety of sensitivity scans are underway.

One interesting aspect of the turbulent physics that can be uniquely probed with the GENE code is the contribution of perpendicular temperature fluctuations (T_{perp}) versus total (T_{perp} and T_{parallel}) temperature fluctuations to the measured signals. A comparison of the perpendicular and total contributions is shown in Figure 3. The synthetic diagnostic (based on antenna pattern measurements) has been applied to the GENE output in both cases, and these two spectra are overplotted with the experimental spectrum. This result, that the total fluctuation level agrees better with the experiment, is the subject of ongoing investigation.

2.3.4 Upgraded hardware and initial results from 2017 run campaign

One of the last milestones of the original subcontract, was the completion of the design and construction of a new 30-channel CECE receiver, that was shipped to ASDEX in February 2017. The upgraded system now allows for improved radial coverage capabilities, and this summer, we will be examining possible measurements of the radial correlation length (which is a proxy for eddy structure size) as well using the newly upgraded hardware capabilities.

As we close out this DOE award, and the subcontract with IPP, we are looking forward to a new subcontract on our new DOE award to carry this very successful collaboration forward. In April, MIT will begin new two year collaboration, funded by a new US DOE contract (White, Principal Investigator) and work continues on a new receiver for use with the nT phase diagnostic (with more tunable radiometer channels), along with continued use of the CECE diagnostic, at AUG.

2.3.5 Future Work on Cross-Machine Validation of Core Transport Models

The CECE and model validation project at Alcator C-Mod funded by this award ended in September 2016, when the final Alcator C-Mod campaign ended. A successful transition of the team from C-Mod to AUG has taken place, with a growing CECE/nT phase and model validation project now in place at AUG. The current collaboration with ASDEX Upgrade is funded by a new contract from DOE FES, and is a major endeavor for MIT. Our team is also heavily involved with transport model validation efforts at the DIII-D tokamak (funded under a separate contract). Through these collaborations and other synergistic efforts at MIT, we have plans to investigate these topics in the near term as part of cross-machine validation efforts.

1. Transport Shortfall

Revisit the DIII-D shortfall, and compare DIII-D L-mode plasmas to C-Mod and ASDEX Upgrade, using data from the new CECE system as well as measurements of the profile stiffness where applicable. We will run TGLF and GYRO and GENE as part of these three machine CECE validation efforts.

2. LOC/SOC : the role of ITG/TEM turbulence

Provide CECE data from Alcator C-Mod to other groups around the world studying the LOC/SOC transition. Data from the new CECE diagnostic at ASDEX Upgrade will also be made available as needed.

3. Intrinsic rotation reversals : the role of ITG/TEM turbulence

Provide CECE data from Alcator C-Mod to other groups around the world studying intrinsic rotation reversals. Data from the new CECE diagnostic at ASDEX Upgrade will also be made available as needed.

4. Effects of multi-scale physics in L-mode and I-mode

We will use TGLF modeling, CECE fluctuation data, and profile stiffness where available to compare TGLF-SAT1 performance in L-mode and I-mode plasmas at DIII-D, C-Mod, and AUG. Where possible, we will also use nonlinear GENE and GYRO simulations as part of this validation effort.

5. nT phase measurements and predictions: We will compare the nT phase measurements from DIII-D and AUG with each other and with predictions from TGLF and nonlinear GENE and GYRO simulations.

2.4 Conclusions

Working first with the MIT team on making new CECE measurements in C-Mod (2011-2016), and the many associated validation efforts, and then working with IPP making new CECE and nT phase measurements in ASDEX Upgrade (2015-present), has been an excellent experience. The project at C-Mod explored the validity of predictive models for ITER in a unique and reactor relevant regime, and the current endeavor at AUG is opening new avenues of physics discovery and is helping establish a long-term partnership between the US fusion community and IPP. Despite the loss of C-Mod for the US program, we hope that this collaboration project with IPP will continue and will allow for expanded opportunities for US undergraduate and graduate students in the future to perform research in Germany at one of the premiere tokamak experiments in the world. We anticipate that in Fall 2017, we will have a new MIT grad student begin work on the CECE/nT phase project, bringing manpower commitment to project to new high level (Freethy (on site at AUG), Creely PhD at MIT, new student PhD at MIT, engineers Terry and Burke at MIT, Prof. White at MIT). We look forward to continued collaboration with IPP and further growth of this exciting project in support of turbulent transport physics and model validation thrusts at AUG.

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Section 4: Publically Accessible References

4.1 Refereed Journal Articles and Student Theses

This list is in chronological order. These refereed journal articles are all publically accessible through the MIT Libraries (<http://library.psfc.mit.edu/>). The ** denotes authors who are students at MIT. This project has resulted in one PhD thesis, two MS theses, and one undergraduate BS thesis, which are included in this list. There are 33 publications, 29 excluding the theses.

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4.2 Selected Conference Presentations

These are listed alphabetical by author. These presentations are all publically accessible at the MIT PSFC webpage (<http://www-internal.psfc.mit.edu/research/alcator/pubs/index.htm>). We have included only the most pertinent conference presentations (28 listed here) from graduate and undergraduate students and postdocs in the group.

1. A. J. Creely, Invited Speaker: Multi-Channel Validation of Nonlinear Gyrokinetic Simulations in Alcator C-Mod I-mode Plasmas, in the 58th Annual Meeting of the APS Division of Plasma Physics, 2016.
2. A.J. Creely, A.E. White, G. Conway, S. Freethy, N.T. Howard, and A.E. Hubbard, Electron Temperature Fluctuations and Profile Stiffness in Alcator C-Mod L-mode and I-mode Plasmas, in the US Transport Task Force Workshop, 2016.
3. A. J. Creely, E. M. Edlund, N. T. Howard, A. E. Hubbard, and A. E. White, Perturbative Thermal Transport Studies on Alcator C-Mod, in the 57th Annual Meeting of the APS Division of Plasma Physics, 2015.
4. A. J. Creely, E. M. Edlund, N. T. Howard, A. E. Hubbard, and A. E. White, Heat Pulse Thermal Diffusivity from Partial Sawtooth Crashes in Alcator C-Mod L-mode and I-mode Plasmas, in the US/EU Transport Task Force Workshop, 2015.
5. A. J. Creely, E. M. Edlund, N. T. Howard, A. E. Hubbard, and A. E. White, Heat Pulse Thermal Conductivity in Alcator C-Mod L-mode and I-mode Plasmas, in the 56th Annual Meeting of the APS Division of Plasma Physics, 2014.
6. S.J. Freethy *et al.*, Invited oral – “Measuring turbulent-field fluctuation amplitudes, frequency spectra, correlation lengths and phase angles using 75-120 GHz on ASDEX Upgrade”, 2nd Microwaves in Plasmas and Beams workshop (2016)
7. S.J. Freethy *et al.*, Poster – “Measurement of turbulent electron temperature fluctuations on ASDEX Upgrade”, 58th Annual Meeting of the APS Division of Plasma Physics (2016)
8. S.J. Freethy *et al.*, Invited oral – “The role of theoretical predictions in the design of correlation ECE and nT cross-phase diagnostics”, 21st Joint EU-US Transport Task Force Meeting (2016)
9. S.J. Freethy *et al.*, Poster – “Measurement of turbulent electron temperature fluctuations on ASDEX Upgrade”, 21st Topical conference on high temperature plasma diagnostics (2016)
10. S.J. Freethy *et al.*, Poster – “Measurement of turbulent electron temperature fluctuations on ASDEX Upgrade”, 43rd European Physical Society conference on plasma physics (2016)
11. S.J. Freethy *et al.*, Invited oral – “Measuring turbulent temperature fluctuations and their relationship to density fluctuations in tokamak plasmas”, 1st Microwaves in Plasmas and Beams workshop (2015)

12. S.J. Freethy *et al.*, Poster – “Development progress of Correlation ECE and nT cross-phase diagnostics for ASDEX Upgrade”, 57th Annual Meeting of the APS Division of Plasma Physics (2015)
13. S.J. Freethy *et al.*, Oral – “Electron kinetics from microwave bursts during Edge Localised Modes in MAST”, 42nd European Physical Society conference on plasma physics (2015)
14. S.J. Freethy *et al.*, Invited oral – “Electron kinetics inferred from observations of microwave bursts during edge localised modes in the Mega-Amp Spherical Tokamak” 42nd IOP Plasma Physics Conference (2015)
15. S.J. Freethy *et al.*, Oral – “Development progress of Correlation ECE and nT phase-angle diagnostics for AUG”, 12th International Reflectometry Workshop (2015)
16. C. Oi, C. Sung, N. Howard, A. E. White, J. Irby, R. Leccacorvi, R. Vieira, J. Rice, C. Gao, *Studies of Electron Temperature Fluctuations in the Core of Alcator C-Mod Plasmas via Correlation ECE*, American Physical Society - Division of Plasma Physics, Providence, RI, USA, October 29-November 2, 2012
17. C. Sung, A. E. White, N. T. Howard, D. Mikkelsen, C. Holland, J. Rice, M. Reinke, C. Gao, P. Ennever, M. Porkolab, R. Churchill, C. Theiler, J. Walk, J. Hughes, A. Hubbard, M. Greenwald, and the Alcator C-Mod team, "Validation study of gyrokinetic simulation (GYRO) near the edge in Alcator C-Mod ohmic discharges," 56th Annual Meeting of the American Physical Society Division of Plasma Physics, 2014
18. C. Sung, A. E. White, N. T. Howard, D. Mikkelsen, J. Irby, R. Leccacorvi, R. Vieira, C. Oi, J. Rice, M. Reinke, C. Gao, P. Ennever, M. Porkolab, R. Churchill, C. Theiler, J. Walk, J. Hughes, A. Hubbard, M. Greenwald, and the Alcator C-Mod team, "Correlation ECE diagnostic in Alcator C-Mod: Explore LOC/SOC transition physics," Seminar to plBBma research group in Seoul National University, 2014
19. C. Sung, A. E. White, N. T. Howard, D. Mikkelsen, J. Irby, R. Leccacorvi, R. Vieira, C. Oi, J. Rice, M. Reinke, C. Gao, P. Ennever, M. Porkolab, R. Churchill, C. Theiler, J. Walk, J. Hughes, A. Hubbard, M. Greenwald, and the Alcator C-Mod team, "Correlation ECE diagnostic in Alcator C-Mod: Explore LOC/SOC transition physics," Seminar to KSTAR group, 2014
20. C. Sung, A. E. White, N. T. Howard, D. Mikkelsen, J. Irby, R. Leccacorvi, R. Vieira, C. Oi, J. Rice, M. Reinke, C. Gao, P. Ennever, M. Porkolab, R. Churchill, C. Theiler, J. Walk, J. Hughes, A. Hubbard, M. Greenwald, and the Alcator C-Mod team, "Correlation ECE diagnostic in Alcator C-Mod: Explore LOC/SOC transition physics," 18th Joint Workshop on Electron Cyclotron Emission and Electron Cyclotron Resonance Heating, 2014

21. C. Sung, A. E. White, N. T. Howard, D. Mikkelsen, J. Rice, M. L. Reinke, C. Gao, P. Ennever, M. Porkolab, R. Churchill, C. Theiler, J. Walk, J. Hughes, A. Hubbard, M. Greenwald and the C-Mod team, "Changes in turbulence and transport across the ohmic confinement transition," International Sherwood Fusion Theory Conference, 2014
22. C. Sung, A. E. White, N. T. Howard, D. Mikkelsen, J. Rice, M. L. Reinke, C. Gao, P. Ennever, M. Porkolab, R. Churchill, C. Theiler, J. Walk, J. Hughes, A. Hubbard, M. Greenwald and C-Mod team, "Studies of the Ohmic Confinement Transition through Turbulence Measurements and Comparison with Gyrokinetic Simulations," 55th Annual Meeting of the American Physical Society Division of Plasma Physics, 2013
23. C. Sung, A. E. White, N. T. Howard, C. Y. Oi, J. E. Rice, M. L. Reinke, C. Gao, P. Ennever, M. Porkolab, F. Parra, D. Mikkelsen, D. Ernst, J. Walk, J. W. Hughes, J. H. Irby, C. Kasten, A. E. Hubbard, M. Greenwald and C-Mod team, "Study of Ohmic Energy Confinement Transition through Core Electron Temperature Fluctuation Measurements and Gyrokinetic Analyses in Alcator C-Mod," Seminar to ASDEX-U group, 2013
24. C. Sung, A. E. White, N. T. Howard, C. Y. Oi, J. E. Rice, M. L. Reinke, C. Gao, P. Ennever, M. Porkolab, F. Parra, D. Mikkelsen, D. Ernst, J. Walk, J. W. Hughes, J. H. Irby, C. Kasten, A. E. Hubbard, M. Greenwald and C-Mod team, "Study of Ohmic Energy Confinement Transition through Fluctuation Measurements and Gyrokinetic Analyses in Alcator C-Mod," U.S.-E.U. Joint Transport Task Force Workshop, 2013
25. C. Sung, A. E. White, N. T. Howard, C. Y. Oi, J. Rice, M. Reinke, C. Gao, J. Walk, J. Hughes, A. Hubbard, P. Ennever, M. Porkolab, M. Greenwald and C-Mod team, "First Measurements of Core Electron Temperature Fluctuations in Alcator C-Mod via Correlation ECE," 54th Annual Meeting of the American Physical Society Division of Plasma Physics, 2012
26. C. Sung, A. E. White, J. Irby, R. Vieira, R. Leccacorvi, C. Y. Oi, W. A. Peebles, X. Nguyen, "Correlation Electron Cyclotron Emission Diagnostic for Alcator C-Mod : Design and First Results," 19th Ibpical Conference High Temperature Plasma Diagnostics, 2012
27. C. Sung, A. E. White, J. Irby, R. Vieira, R. Leccacorvi, B. Labombard, J. Goh, W. A. Peebles, X. Nguyen, "New Correlation Electron Cyclotron Emission Temperature Fluctuation Diagnostic for Alcator C-Mod," 53rd Annual Meeting of the American Physical Society Division of Plasma Physics, 2011

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