Validating electromagnetic turbulence and transport effects for burning plasmas

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EXECUTIVE SUMMARY

Developing a sustainable fusion energy source requires long-time, steady-state plasma conditions, typically achieved with high bootstrap fraction at high beta. Developing cost-effective devices, such as a compact Fusion Nuclear Science Facility (FNSF), also requires simultaneous high beta and high confinement. At higher beta the influence of electromagnetic effects on transport, turbulence and confinement becomes increasingly important. Our understanding of, and ability to predict, these effects significantly lags that of electrostatic effects. This dramatically reduces the applicability of current predictive models for high performance, high-beta plasmas, limiting the ability to optimize the performance of present tokamaks, ITER and possible future devices.

A new initiative is proposed to invest in enhanced diagnostic, simulation, and analysis efforts, specifically to validate the physics of electromagnetic effects on turbulence and transport. This initiative will dramatically improve the accuracy and fidelity of transport predictions. Such an investment would allow the US to retain world leadership in validation of transport and turbulence physics, and corresponding development of predictive models, over a wider range of plasma discharge conditions, particularly those relevant for high performance, steady-state burning plasma regimes. Results would be maximized with substantial enhancement in funding (~$4.5M/year): the impact of incremental funding would be significant given the existing base of facilities, diagnostics, simulation codes and analysts in the US.

BACKGROUND

Developing a sustainable fusion energy source, one of the key goals of the DOE Office of Fusion Energy Sciences (DOE-FES), requires the ability to predict long-time, steady-state plasma conditions for ITER and next-generation devices to ensure safe operation (for safe start-up and ramp-down, to avoid disruptions & large heat fluxes to the walls, etc…). Having this predictive ability will also aid optimization of next-generation devices, such as a Fusion Nuclear Science Facility or DEMO.

Developing long pulse, high-performance tokamak scenarios requires optimizing confinement of the plasma with profiles that are consistent with a steady-state, non-inductive equilibrium, which usually requires high bootstrap fraction at high beta. Therefore, one of many elements required for predicting integrated scenarios is developing a transport model that is accurate across the relevant range of parameter space. Such a model must capture the appropriate scaling of all relevant transport mechanisms, requiring it to be physics-based (as opposed to empirical).

As an example, first-principles gyrokinetic turbulence simulations are considered to be the state-of-the-art for representing core turbulence and transport. They need to be validated by turbulence and transport measurements to provide the assurance that they accurately recover experimental observation. However, these simulations are very computationally expensive, especially if used to predict plasma profiles [Barnes:2010, Candy:2009]. Therefore, development of "reduced" physics-based transport models are often pursued, which themselves must also be validated to ensure accurate representation of the first-principles simulations, as well as experiment.

Much progress has been made in developing and validating first principles turbulence simulations and reduced transport models in the electrostatic (ES) limit (β=0), i.e. a limit that ignores the influence of magnetic fluctuations (δB=0). However, there is experimental and theory/simulation work that illustrates the importance of finite-β, electromagnetic (EM) effects on transport and turbulence, especially as plasma beta is increased.

<u>EM EFFECTS ON TRANSPORT AND TURBULENCE</u>

It has been known that increasing beta can be stabilizing to traditionally electrostatic turbulence mechanisms such as ion temperature gradient (ITG) and trapped electron modes (TEM). This has been shown for a dedicated validation exercise in DIII-D H-mode and QH-mode discharges [Holland:2012b] using gyrokinetic simulations. Surprisingly, this effect can be enhanced in the presence of a substantial fast ion population, especially in nonlinear simulations [Citrin:2013], illustrating the importance of validating gyrokinetic simulations with finite-β and significant beam ion fractions and/or fusion α's. Using the TGLF reduced transport model [Staebler:2005,2007], fusion power predictions for ITER are larger (5-20%, depending on assumptions of density peaking) when including finite beta effects (β_N=1.8) [Kinsey:2011]. Stronger stabilizing effects are predicted for DIII-D hybrid scenarios at even higher normalized beta, β_N>3 [Kinsey:2010]. <u>It becomes increasingly important to validate EM effects on transport and turbulence for scenarios with increasing β, and populations of fast ions, as these are typically the regimes envisioned for high-performance, non-inductive, steady-state scenarios necessary for long-pulse tokamak reactors.</u>

> *A new initiative is proposed to enhance validation efforts that specifically focus on the importance of electromagnetic effects relevant to transport mechanisms and turbulence.*

Increasing beta is expected to cause larger amplitude magnetic perturbations (δB/B). Through field line-bending these perturbations are stabilizing to the traditional electrostatic instabilities, as discussed above. But at larger beta, fundamentally new EM instabilities arise with characteristics unique from the ES mechanisms. One such mechanism is the microtearing (MT) mode, which has been predicted in the core of conventional tokamaks like ASDEX-UG [Vermare:2007, Doerk:2012], DIII-D [Petty:2012], and JET [Moradi:2013]; spherical tokamaks like MAST [Applegate:2007] and NSTX [Wong:2007]; and reversed field pinches (RFPs) like RFX [Predebon:2010] and MST [Carmody:2013]. The microtearing mode has also been predicted to occur near the top of H-mode pedestal in MAST [Dickinson:2012], NSTX [Canik:2013], JET [Saarelma:2012] and for model ITER profiles [Wong:2010]. An additional electromagnetic mechanism that arises is the kinetic ballooning mode (KBM), which is predicted to occur in the core of high-beta plasmas in NSTX [Guttenfelder:2013] and the LHD stellarator [Ishizawa:2014]. The KBM is also a key mechanism (in conjunction with the ideal MHD peeling-ballooning modes) used in a successful model for tokamak H-mode pedestals [Snyder:2011]. The related resistive ballooning mode (RBM) can develop at higher collisionalities, e.g. at the bottom of the H-mode pedestal and into the scrape-off layer [Bourdelle:2012, Myra:2000, Rafiq:2010, Rogers:1998]. Finally, although traditionally only investigated for their effects on fast ion transport and redistribution, multiple excitations of global and compressional Alfven eigenmodes (GAE/CAE) by NBI fast ions are predicted to cause significant levels of anomalous radial electron thermal transport in high power NSTX discharges [Gorelenkov:2010; Tritz:2012]. A large number of mechanisms influencing transport and confinement for high beta, high performance plasmas are fundamentally electromagnetic in nature.

> *A critical element in this initiative is to develop and implement diagnostics capable of measuring internal δB, across a range of devices and parameters, to help identify and distinguish the fundamentally unique characteristics of various electromagnetic mechanisms predicted to influence confinement in toroidal fusion plasmas.*

A broad range of parameter space is encompassed by the diversity of toroidal confinement devices (conventional aspect ratio R/a≈3 tokamaks, like DIII-D and Alcator C-Mod; spherical tokamaks R/a≈1.5, like NSTX-U; reversed field pinches, like MST). The behavior of the various transport mechanisms discussed above, in particular at different beta and aspect ratio, influences performance in distinct ways. One key empirical example is the difference in multi-machine confinement scaling with dimensionless variables β and collisionality (ν_*). In spherical tokamaks global thermal confinement has been observed to scale as $B\tau_E \sim \nu^{-0.9}\ \beta^{-0.2}$ [Kaye:2007,2013; Valovic:2009,2011], in contrast to that encompassed in ITER 98y,2 ELMy H-mode scaling $B\tau_E \sim \nu^{0}\ \beta^{-0.9}$ [Doyle:2007]. The variation in confinement scaling has strong implications when designing the operating point of next-generation devices (e.g. [Petty:2008, Chan:2010, Valovic:2011] and whitepaper by Maingi). While some level of transport modeling has been done for the various identified transport mechanisms they have usually been done in isolated limits. One unified treatment has not been identified that has been validated against the broad range of confinement results across different machines and operating space, e.g. that can recover the variation in confinement scaling.

> *To achieve optimal design and operation of next-generation devices it will be critical to develop validated transport models that span the relevant range of parameters envisioned, including aspect ratio and beta (Fig. 1).*

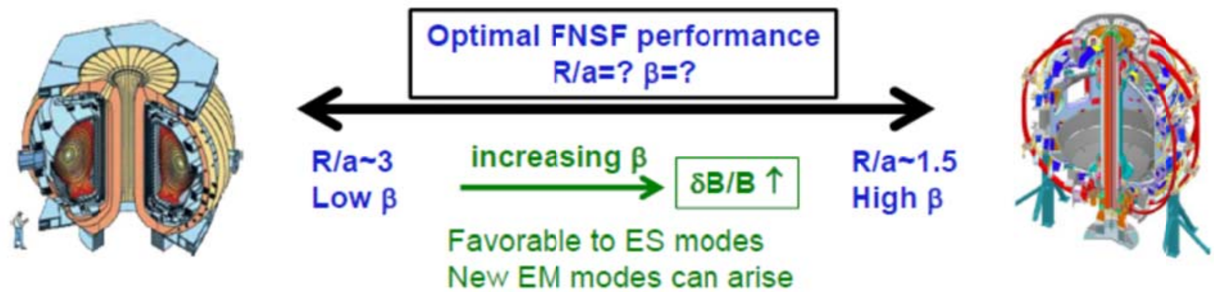

Fig. 1. Finite-β, electromagnetic effects manifest themselves in different ways depending on toroidal configuration and beta. Understanding these effects for various transport mechanisms, through theory and simulation validated by measurements, is critical to develop reduced transport models that can then be used to aid design and optimization (e.g. over aspect ratio and beta) of future devices like ITER, FNSF, and DEMO.

A new initiative to (i) enhance validation efforts that specifically focus on the importance of electromagnetic effects on transport and turbulence, with emphasis on (ii) developing and implementing diagnostics capable of measuring internal magnetic fluctuations across a diversity of devices and parameters to help identify and distinguish the unique mechanisms, and (iii) development of validated reduced transport models for these mechanisms, addresses many goals, priorities and gaps identified within Fusion Energy Sciences:

DOE-FES Mission and Goals:
"Advance fundamental science of magnetically confined plasmas to develop predictive capability needed for a sustainable fusion energy source."

Synakowski Challenges (April 9, 2014: *The charge for advice on strategic planning*)
"Burning Plasma Science: Foundations – Understand the fundamentals of transport, macro-stability, wave-particle physics, and plasma-wall interactions."

FESAC Report on Priorities, Gaps and Oportunities (2007)
"G1 – Sufficient understanding of underlying plasma physics to predict the performance and optimize design and operation of future devices" (e.g. ITER, FNSF, DEMO).

In particular, the 2007 FESAC Report recommended a major initiative to address this gap: "I-1. Initiative toward predictive modeling and validation", including: "Combine advances in simulations with vigorous efforts to validate with experiments…" and "A critical element would be development and deployment of new measurement techniques".

FESAC ReNeW Report (2009)
"ReNeW Thrust 6: Develop predictive models for fusion plasmas, supported by theory and challenged with experimental measurements".

RECENT PROGRESS AND CHALLENGES

The process of validation requires using all available measurements to compare with accurate, high-fidelity theory and simulation predictions, checking for agreement within experimental uncertainties while taking into account model sensitivities (e.g. [Greenwald:2010]). To make a faithful comparison requires applying synthetic diagnostics to the simulation output to account for a given diagnostic instrument function, wavenumber selectivity, etc…

Measurements

Core turbulence validation efforts have utilized various diagnostics to measure predominantly density fluctuations (BES, DBS, reflectometry, high-k microwave scattering) and electron temperature fluctuations (CECE). It has been challenging to measure internal magnetic fluctuations in hot tokamak plasmas. However, it is desirable to have a direct measure of the turbulent magnetic fluctuations as they are an integral part of the various mechanisms discussed above, and can be used to help experimentally distinguish them from electrostatic turbulence (e.g. change in amplitude and spatial structure with beta), providing additional validation constraints on theory/simulation. Recent progress has been made in a number of diagnostic techniques that show promise for future development, each with their own advantages.

The polarimetric measurement of the Faraday effect can be exploited to isolate the radial component of the magnetic fluctuation. Recent results at Alcator C-Mod and DIII-D have found that polarimetry measurements are sensitive to high-frequency broadband fluctuations. While polarimetry can be sensitive to δB, the measurement is line-integrated, and *clarifying whether these measurements are from* δB*,* δn *or a combination of both requires further investment to obtain simultaneous polarimeter + interferometer measurements, with more spatial chords*. Such a method has been pioneered on the reversed field pinch MST to measure spatial features of turbulent internal magnetic fluctuations, density fluctuations, as well as the δn-δB correlation for tearing modes [Brower:2001,Ding:2009,Lin:2014]. Measurement of the phase between fluctuating quantities provides a higher-order constraint on code output which is critical for validation, *but further development is required to achieve such a measurement for smaller scale microturbulence*. It is noted that the polarimeter implemented on DIII-D will be installed on NSTX-U. Using a synthetic diagnostic applied to microtearing simulations to mimic the measurement predicted that the polarimeter should be sensitive to δB from microtearing modes, in the regime simulated [Zhang:2013]. In addition, a new 700 GHz polarimeter-interferometer is being built for DIII-D with installation planned in 2015.

Cross polarization scattering (CPS) [Lehner:1989,Vahala:1992] is another technique to infer internal magnetic fluctuations, which provides spatial and wavenumber localization. It was originally developed in the 1990's at Tore Supra [Zou:1995, Colas:1998] but has recently been revisited on both MAST [Hilleshiem:2013] and DIII-D [Rhodes:2014]. Initial measurements find broadband fluctuations that behave distinctly from density fluctuations and are consistent with expectations for successfully isolating the cross-polarized radiation, implying the measurement is dominated by δB. These are preliminary results and *further work is necessary to confirm them*.

There are other possible techniques that have been proposed or implemented for internal magnetic measurements, including Li-beam [Stoschus:2013] and MSE [Suzuki:2008]. In many cases, non-turbulent (slow time scale) δB measurements have been achieved, *but require additional development for routinely diagnosing broadband magnetic fluctuations*.

Simulations

Electrostatic first-principles nonlinear turbulence simulations have become more physically realistic, using ever increasing resolution, model accuracy (geometry, impurity species, …), and computational resources. This has allowed for validation of turbulence characteristics and transport with quantitative accuracy within uncertainties, at least in some instances (e.g. [Holland:2009,Howard:2012a,White:2013,Told:2013]). Including electromagnetic perturbations and associated physics adds additional complications. For example, achieving well resolved, saturated nonlinear microtearing simulations has only recently been demonstrated [Doerk:2011; Guttenfelder:2011] after initial attempts uncovered numerical difficulties [Applegate:2006]. While nonlinear gyrofluid simulations of KBM turbulence were presented 15 years ago [Snyder:2001], gyrokinetic simulations have been challenged by so-called "runaway" [Pueschel:2008,2010], with transport saturating at very large values. While different physical saturation mechanisms have been proposed [Waltz:2010; Pueschel:2013], experimental validation of these theories remains to be demonstrated. The electromagnetic simulations, especially microtearing, require significant expansion in numerical resolution, and therefore computational resource, to obtain physically meaningful results. Even with expanded resolution and resource there are still cases where nonlinear EM codes seem to be challenged, often encountering numerical instability. This can occur even for the relatively low beta scenarios [Holland:2012b]. *Overcoming these challenges requires dedicated effort and computational resource simply to test various numerical schemes, resolution, and model assumptions (such as boundary conditions) to improve simulation reliability.*

Routine use of nonlinear electromagnetic gyrokinetic codes for validation experiments would benefit from more robust numerical algorithms and ability to efficiently use largest possible core counts to maximize output. *This requires dedicated computational development time*. Recognition of the importance of EM effects has motivated development of upgraded global-EM codes such as GTS, XGC-1 and GTC. Code benchmarking, or verification, is a critical element of this activity to verify the successful implementation into the various codes, *which also requires dedicated resources.*

Synthetic diagnostics

To accurately compare diagnostic measurements with simulation results for validation exercises it is necessary to compare quantities that are as equivalent as possible. This is accomplished through using synthetic diagnostics, applying an appropriate instrument function, wavenumber selectivity, etc… to simulation data to best mimic the diagnostic measurement. In the recent past this has been used for validation exercises that include measurements from beam emission spectroscopy (BES) [Holland:2009], Doppler backscattering (DBS) [Holland:2012a] and phase contrast imaging (PCI) [Ernst:2006] for density fluctuations, and correlation electron cyclotron emission (CECE) for electron temperature fluctuations [White:2008].

Using synthetic diagnostics allows for more accurate planning and development of dedicated validation experiments, providing an *a priori* blind prediction uninfluenced by previous knowledge of experimental results. This can be used to identify sensitive tests that provide the greatest leverage for validating the theory/simulation predictions within the limitations of a given diagnostic. E.g. by applying a synthetic diagnostic approach to mimic a polarimeter diagnostic [Zhang:2013] it was found that such a diagnostic could be sensitive to magnetic fluctuations due to microtearing turbulence as predicted from nonlinear simulations. *Similar analysis can be used to optimize and prioritize new diagnostic development through scoping studies.*

INITIATIVE

The proposed initiative emphasizes increased focus on validating electromagnetic effects in transport and turbulence, which fits within broader on-going validation efforts (e.g. see whitepapers by Boivin, Brower, White). The time is ripe to pursue such a focused initiative given the maturity of US facilities and recent progress in EM simulations, diagnostic techniques, and general validation procedures.

A key element of the proposed initiative is to coordinate theorists and experimentalists to routinely develop and interface synthetic diagnostics with simulations that would target development of diagnostic capabilities for validation. This would ideally include support for diagnostic scoping studies *prior to prototyping and implementation*. This can be used to identify, within the limitations of given diagnostics, what measurements provide the greatest leverage for validating theory and simulation predictions. For example, it should be possible to identify which system (multi-chord polarimeter/interferometer, cross polarization scattering, Li-beam, etc…) is likely to be more or less sensitive to internal magnetic fluctuations for a given facility, depending on operating regime, physical mechanisms predicted to be at play, diagnostic access, etc... The scoping studies would consider simultaneously other available turbulence measurements (BES, DBS, PCI, high-k scattering, CECE, …) presently available or planned at US facilities. Considering multiple diagnostics allows for correlation analysis among unique measurements that can be used to distinguish particular physical mechanisms (e.g. as was done with ne-Te cross phase measurements [White:2010]). Such advanced correlation analysis could alter which new diagnostic will provide the most sensitive test to validate various electromagnetic mechanisms. A natural part of the scoping study would be to expand ongoing experimental validation efforts, which requires increased support for running fully electromagnetic simulations.

The scoping exercises can, and should, also be influenced by additional physics topics outside the area of core turbulence and transport, including H-mode pedestal and ELM physics, core MHD physics, disruptions/precursor detection, etc… Thinking more broadly will also likely influence the ideal choice of diagnostic system, configuration, desired number of channels, etc…

A subsequent key element of the initiative will be to design and implement new, or upgrade present, diagnostics at appropriate facilities to aid the measurement of internal magnetic fluctuations. The scoping studies above, with sufficient priority and investment, will ideally influence the decision-making process, although investment in new and upgraded diagnostics should occur regardless of this effort.

To allow for effective validation tests it will be necessary to improve the efficacy and reliability of electromagnetic turbulence simulation codes for a wide range of plasma parameters (as encompassed by the diversity of operating facilities and ITER). This must span the codes necessary to simulate all transport mechanisms expected to be important (gyrokinetic codes for core turbulence, hybrid-MHD codes for Alfven eigenmodes, gyrofluid codes for edge/SOL, …). This includes improving existing codes and possibly developing new codes, with resources for computational experts to improve numerical algorithms and scalability on high performance computing systems. Additional labor is required to carry out appropriate verification (code-benchmarking) tests, as well as to create the often-neglected clear and informative documentation to support a strong user base. These tasks represent an immense effort and it is expected that a significant part of these would be covered by corresponding simulation initiatives (e.g. see whitepapers by Chang, Fu, Hammett, Snyder, Tang, Xu). Ideally, EM simulations need to be reliable for effective systematic validation tests by non-developers.

With the ultimate goal of improving predictive capability, it is critical that sufficient effort be given to the development and validation of reduced transport models (e.g. TGLF, MMM, …). While a solid base of work exists in this area, additional investment is required to comprehensively validate the importance of electromagnetic effects. Demonstrating useful predictive capability requires a given model (or set of models, used in an appropriately constructive way) span a wide range of plasma parameters, such as that encompassed by US facilities and ITER.

Cost

Significant progress in this initiative will be obtained over ten years with substantial increases in:
(i) diagnostic development and implementation ($2M/year, hardware and labor)
(ii) validation experiments & running corresponding simulations ($1M/year, ~3 FTE/year)
(iii) development and integration of synthetic diagnostics with simulations ($0.5M/year, ~1.5 FTE/year)
(iv) development and improvement of electromagnetic simulation and modeling capabilities ($1M/year, ~3 FTE/year)

For maximum effect FES would invest up to $4.5M/year. These efforts obviously fit within broader on-going validation efforts and significant impact could be recognized with incremental funding as there exists already a strong base of facilities, diagnostics expertise, simulation codes and analysts. With a more coordinated approach, e.g. creation of dedicated “validation teams” (whitepaper by White), resources could be used most effectively.

WHY NOW

Given the progress in diagnostic measurements, simulations and modeling, the time is ripe to invest in more dedicated validation of transport and turbulence, specifically including the impact of electromagnetic effects. These efforts should take advantage of the maturity and diversity of present US facilities, as the nuclear environment expected in future burning plasma devices will make it challenging, if not impossible, to implement many diagnostics desired for validation exercises. Delaying these validation efforts dramatically slows the improvement, and therefore utility, of predictive models, which ultimately limits the FES community’s ability to provide the necessary physics basis to optimize design and operation of future devices.

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