A Hierarchal Approach to Validation Experiments in Magnetic Fusion Science

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Introduction

The capability for predictive modeling of fusion plasmas is a key goal for the MFE program, but is still far from being realized. Predictive capability will not be easily attained because understanding of the complex dynamics of plasmas in nontrivial magnetic confining geometries is incomplete and there are well-known difficulties attendant to completing that understanding. Some of the difficulties are common to complex systems, like intrinsic nonlinearity and multiple scales. In plasmas these are exacerbated by other complexities. No single model or set of equations describes the physics, rather the dynamics can only be described by various models, each with different physics, governing equations and physical scales. Moreover, there are multiple equilibria, bifurcation paths, extreme sensitivity, and limitations in measurement capabilities. The task of achieving predictive capability can be framed as a rigorous validation effort, preceded by appropriate verification. The elements presently anticipated for such a validation effort in fusion plasma science have recently been considered [1] as an extension of validation science in related fields [2]. We will not review these elements here, but instead focus on one aspect of validation in fusion that has received little thought and is particularly challenging.

Validation as realized in other fields employs a set of experiments structured hierarchically to reduce complexity in physics and physical geometries in the validation process. For example, key elements of the physics of internal combustion pursuant to reducing engine emissions have been isolated in experiments that employ a combustion jet removed from bounding surfaces [3]. The complex dynamics of multiple-phase turbulent flow in a system with a large number of reacting chemical constituents is thus detached from the complexities of boundary layer flows on complicated bounding surface geometries. Computational modeling of the combustion physics can thus be validated free of the complications associated with the boundary conditions. Isolation from bounding surfaces can also facilitate diagnostic access. There are similar examples in aerospace and hydrodynamics.

A number of issues make it difficult to reduce complexity in fusion experiments or otherwise enhance diagnostic access in a completely analogous fashion to the examples from other fields. These issues occur because simplified geometries, situations in which physics can be isolated, and regimes with improved diagnostic access often change the physics in fundamental ways rather than simply reduce complexity. Simplifications in geometry can degrade confinement, leading to cold ions and the dominance of neutral collision processes. Simplifying field topologies can introduce line tying, sheath structures, and parallel connection lengths unlike those of operating regimes in performance-class plasmas. Reduction of experimental scale dramatically affects key scaling parameters like the normalized gyroradius ρ_*. Frequently there is also a lack of appropriate computational models for detailed validation in experiments that reduce complexity, isolate physics, or enhance access. These difficulties must be dealt with in the experimental design. For example, experiments can identify ways to make the unwanted effect less critical, the effects can be treated sequentially across more than one experiment, and validation can focus on or develop tests and that are less sensitive to the unwanted effect.

In this white paper we review arguments for why validation on experiments with reduced complexity or enhanced diagnostic access are essential. We discuss the generic requirements for such experiments, and present sketches of several case studies that provide conceptual descriptions of possible experiments.

When models are validated in situations with reduced complexity or enhanced diagnostic access, virtually all of the problems intrinsic to modeling identified in Ref. 1 are lessened. These include discrepancies between model and experiment, fortuitous agreement in comparisons, effects of sensitivity, non-differentiability of models in comparisons with experiment despite differences in physics, and the need to optimize comparisons so that they test targeted, relevant effects. These problems are surmounted because this type of validation is multifaceted, involves multiple experiments, more readily enables multiple measures across a primacy hierarchy [1], and probes more possible manifestations of relevant physics. The breadth of comparisons thus provided optimizes the process of establishing validity. (It should be remembered that models cannot be rigorously proved, but instead are validated by the accumulation of evidence that supports the models, and/or does not contradict them.) Validation in a hierarchy of experiments with reduced complexity also provides a form of stress testing, probing model performance over a range of devices, parameter regimes, and geometries. Performance in such tests quantifies a standard of predictive capability, i.e., that a model does not need to be tuned to remain predictive when applied to different situations within its domain of validity.

Broadly speaking, the type of validation addressed herein requires experiments with one or more of the following features:

1) Interacting or competing physical processes present in the most comprehensive forms of models (apart from geometry) are isolated, allowing model performance for individual pieces to be validated separately. If realizable, experiments that integrate multiple processes are utilized to test sequentially and hierarchically more integrated forms of the model.

2) Model performance for physical processes is validated in simpler geometries or configurations, as part of a sequence of validation experiments working toward complex geometries.
3) Diagnostic access and capabilities are enhanced, allowing more validation measures, and measures with greater significance relative to the physics of a model and its sensitivities.

In the above and subsequent discussion, it is understood that in speaking of experiments, the accompanying models used in validation are expressly adapted to or developed for the experimental configuration and parameters.

In considering these types of experiments it is also noted that confidence in predictive capability is better established if the physics in a model can be tested over its full range of behaviors. For example mode-coupling nonlinearities can yield both coherent and incoherent behavior. If a model is tested and validated for experimental situations that cover both types of behavior the fidelity of the model is more stringently established. Multiple experiments are likely to be needed for validation that samples a full range of behaviors for many physical processes.

High performance devices are the end point of the hierarchy and are therefore essential in validation. However, they cannot take the place of experiments with reduced complexity or enhanced diagnostic access in accomplishing the tasks outlined herein. By their nature, experiments in high-performance devices typically have limitations in diagnostic access, available or achievable diagnostic methods, geometric or operational flexibility, operational run time, and ability to isolate physics. Therefore, specialized validation experiments with one or more of the above features are important in fusion science. There is a natural complementarity between high-performance devices and simpler validation experiments, with the latter providing the base of a validation hierarchy and the former the culmination.

While validation experiments could be sited anywhere, simpler validation experiments provide a compelling potential role for universities in the inevitable evolution of fusion toward larger scale science. Such validation experiments can have infrastructure requirements that are less demanding than high-performance devices, both in hardware and manpower. The emphasis in validation on scientific understanding is compatible with natural concerns of academic research and relates well to the educational mission of universities: validation experiments at universities could serve to provide the fusion program with appropriately trained young scientists. From involvement in properly conceived and executed validation experiments they would be familiar with the key physics elements of fusion science, the expression and measurement of these elements in fusion experiments, the issues attendant to the modeling of fusion plasma dynamics, and the general fidelity of models across the range of expected applications.

Case Studies for Possible Validation Activities

The remainder of this paper presents a series of case studies that illustrate validation activities that could be carried out on laboratory-scale experiments. These activities could be part of a suite of experiments and models with reduced complexity, simplifications in geometry, or enhanced diagnostic capability. Each case study describes a set of validation problems that can be tackled in terms of the physics questions that are to be addressed, the experimental configuration, the types of validation measurements that will be made, requirements for modeling, and how the outcome of these experiments would benefit the science of modeling on high performance devices. The discussion of the experimental configuration describes the advantages offered in reduced complexity, enhanced access, and simpler geometry relative to high performance devices. To balance the discussion it also identifies limitations and describes how these can be dealt with, either by devising comparisons for which the limitations are not critical, or by offsetting them or reducing their impact in some fashion. The discussion of requirements for modeling identifies the adaptations that may be required for existing codes, given the experimental configuration and parameters, or whether new models and codes may need to be developed.

The case studies are not detailed proposals and are necessarily sketchy. They cannot foresee every issue and difficulty that will arise in modeling and in the validation comparisons. Some issues and problems will only become apparent in the process of detailed design or execution of the experiments. The case studies do not constitute a complete, integrated hierarchy across a spectrum of physics complexity. Rather they provide a sampling of experiments that might lie on such a spectrum. The case studies also sample a range of possibilities for validation experiments, from new devices created with specific validation objectives in mind to existing devices, with a description of certain validation missions they could assume. Potential validation missions are a sparse sampling of all possibilities: not every type of validation experiment that might be carried out in a given device or type of device is identified. Until the validation experiments are actually performed, it is not possible to anticipate every way in which they might impact models for high performance devices. However, the validation experiments would address modeling issues of relevance to high performance devices by assessing the completeness of understanding of the physics that goes into any given model. For example, is there missing physics? Where do the models have the greatest difficulty in capturing the physics of the experiments? Validation experiments on simpler devices could also serve to eliminate certain potential sources of discrepancy between model and experiments, showing for example that geometry independent parts of a model algorithm function properly, or that a particular model reduction (say fluid moments of a kinetic operator) performs well in a well controlled plasma scenario.

The case studies necessarily include descriptions that would appear in any proposal for experimentation as it is commonly done. However, the experiments that would be done on the devices of the case studies are not business as usual but carefully planned validation experiments seeking a level of rigor that is yet an ideal in our community. Because it is not an efficient use of space in this paper to repeat in every case study the standards assumed for the validation work, we describe them briefly here. Validation tasks must be an integral part of the design and conception of the experiment. This begins with the identification of physics questions central both to the experiment and to the modeling. This informs the selection of hardware, targeted plasma regimes, and especially diagnostics. Diagnostics appropriate and essential to the validation mission cannot be treated as ancillary or relegated to the status of an upgrade contingency. The models and the codes that generate their numerical representation are also an integral part of developing the experiment from the outset. It is necessary to have appropriate models and coded algorithms that apply to the geometry, configuration, and parameters of the experiment. In some cases this will require routine modifications of existing codes, in some cases it will require major efforts in code development. Models will have to be thoroughly qualified for the experimental configuration. This is the process wherein a theoretical specification is made of the expected domain of applicability of the model and/or approximations made in its derivation. A careful assessment of sensitivities in physics and measurement will be made, and strategies will be developed for how to treat the known sensitivities in the context of validation objectives. Measurements will be evaluated relative a primacy hierarchy and capabilities will be developed for measurement at multiple levels. Validation metrics will be developed and applied to the measurements, and compared with validation on other devices, including high performance devices. If validation is seriously pursued across a suite of devices it is anticipated that new validation approaches not yet devised will be developed for solving challenges confronted in doing validation for fusion plasmas.

The cases studies are arranged as follows:

I. Validation of Boundary Plasma Models on a Small Toroidal Confinement Device

II. Validation of Particle Transport Models in Small Magnetic Confinement Devices with Controlled Fueling Sources

III. Validation of Models for Linear and Nonlinear Dynamics of Edge-Localized MHD Modes

IV. Validation of Edge Turbulence Models via Studies of Turbulence Dynamics in Laboratory Experiments with Open Field Lines

V. Validation of RF Sheath Models

VI. Validating Fundamental Mechanisms of Turbulent Transport in Multiple Channels

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Case Study I. Validation of Boundary Plasma Models on a Small Toroidal Confinement Device

1. Physics questions to be addressed

Boundary plasma physics presents a series of unresolved physics questions that are critical for the goal of practical fusion energy. First, there is a need to understand the physics that sets the boundary layer density and temperature profiles across the transition between open and closed field lines and throughout the scrape-off layer (SOL). These profiles may be a consequence of marginal stability arising from a strong nonlinear dependence of turbulent transport on gradients, leading to profiles that are "stiff" with respect to heat and particle fluxes (Fig.1). Secondly, the structure of the radial electric field in these regions, its origins and its consequences for turbulence and transport are also largely unknown. Closely related is the question of parallel plasma flows, both neoclassical and transport driven, and their role in regulating transport [1]. Third, the magnetic shear, particularly originating from the x-point topology, is predicted to have a large impact on turbulence [2] but this has not been tested experimentally. Finally there is

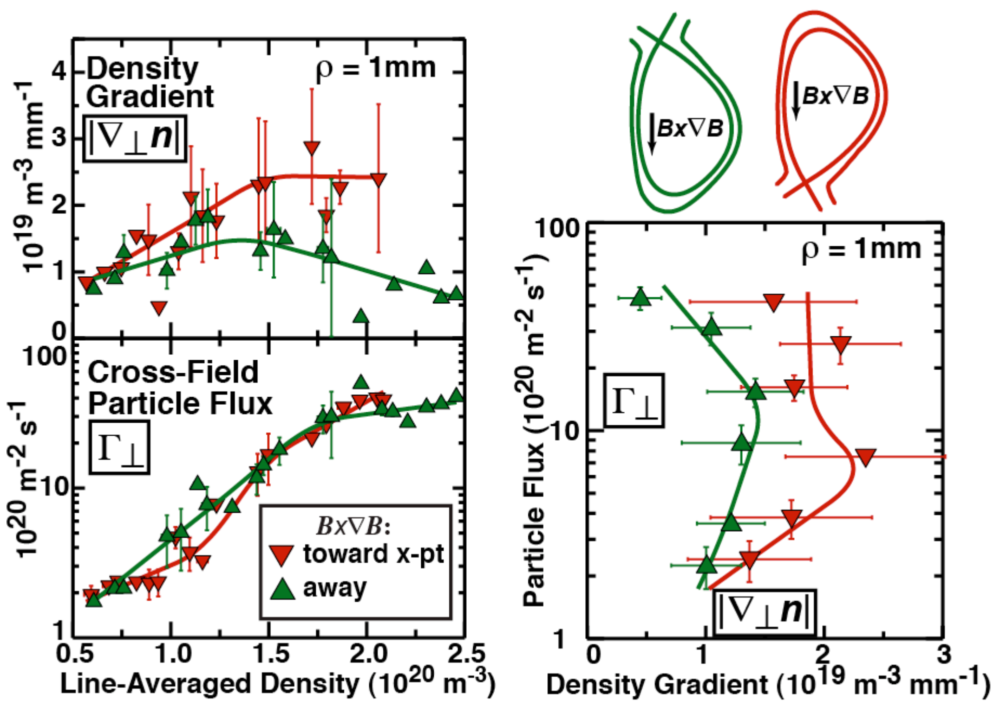

Fig. 1 – Relationship between plasma density gradients and cross-field particle flux densities at a location ~1 mm outside the last-closed flux surface in Alcator C-Mod. Measurements are plotted versus line averaged-density (left) and versus each other (right) [3]. *Data are included from lower single-null and upper single-null topologies with both normal and reversed magnetic fields. A factor of ~20 increase in particle flux is associated with a factor of ~4 increase in line density. Yet, local density gradients increase by only a factor of ~2 or even not at all, depending on the direction of* $B\times\nabla B$. *The resultant flux-gradient relationships (bottom panel) highlight the insensitivity of the gradient to the local flux. Over the full range of fluxes, density profiles appear to be clamped near a 'critical gradient' that depends on the direction of* $B\times\nabla B$. *Edge plasma flows and electric fields also depend on the direction of* $B\times\nabla B$, *suggesting a causal relationship that has yet to be explored.*

a set of issues associated with the sheath boundary condition on open field lines in realistic geometries and how these impacts profiles and heat fluxes in the vicinity of divertor plates and limiters.

These physics questions have a practical impact on fusion devices including the heat and particle loads on plasma facing components; the erosion of the first wall, pumping and fueling requirements and the operational density limit. Since fusion reactors represent a tremendous extrapolation in power loading and pulse length, addressing these problems computationally will require much better physics models. Purely empirical prediction is rather uncertain because it is impossible to simultaneously match SOL and core dimensionless parameters. Improved understanding and predictability will directly affect the operating limits for reactors, the choice of materials, geometry, and the operating temperature for PFCs [4, 5].

2. Experimental configurations

An important subset of the issues outlined above can only be addressed on machines whose magnetic geometry includes both open and closed field lines. That is, we are proposing experiments on laboratory scale toroidal confinement devices. The likely configurations would tokamaks or stellarators that can easily achieve quasi-steady, stable operation. For both types of devices there would be design trade-offs between the strength of the poloidal field, pulse length, diagnostic access and cost. To optimize diagnostic access, it might be most efficient to house the toroidal and poloidal magnets inside a large simple vacuum vessel in the manner of the START device [6].

This class of experiment has a number of advantages for the study of boundary layer physics. They would run with relevant geometry, magnetic shear and divertor geometry and with relevant ratios of parallel and perpendicular scale lengths. Operating at relatively low temperature and density, diagnostic probe access is much improved, allowing collection of a much more complete data set. The ion temperature is finite, though Ti/Te may be lower than in high-performance devices. At the same time, one could expect much higher availability and operational flexibility.

There are limitations to this approach as well. Because the poloidal fields will be relatively low, we can expect stronger neutral interactions with the core and weaker neutral interactions in the SOL compared to high-performance devices. (On the other side of the ledger, enhanced neutral penetration might aid turbulence imaging diagnostics.) For a tokamak, the principle limitation is that the discharges will be pulsed, with pulse lengths shorter, perhaps, than desirable for collection of fluctuation data sets. Simple stellarators, those without quasi-symmetry or quasi-omnigeneity, would have different particle losses and different flow characteristics than tokamaks or optimized stellarators. Stellarators would also need some form of auxiliary heating.

There are options to overcome or mitigate these limitations. For example, it may be possible to limit the effects of neutrals on the plasma core by very strong pumping or wall conditioning. A tokamak design could increase the integrated discharge time and the quality of time-series analysis by optimizing for longer pulse length by increasing the aspect ratio, allowing a larger transformer or by operating at a faster repetition rate. Stellarators, at some cost of complexity and price could be designed with quasi-symmetry and with adequate auxiliary heating.

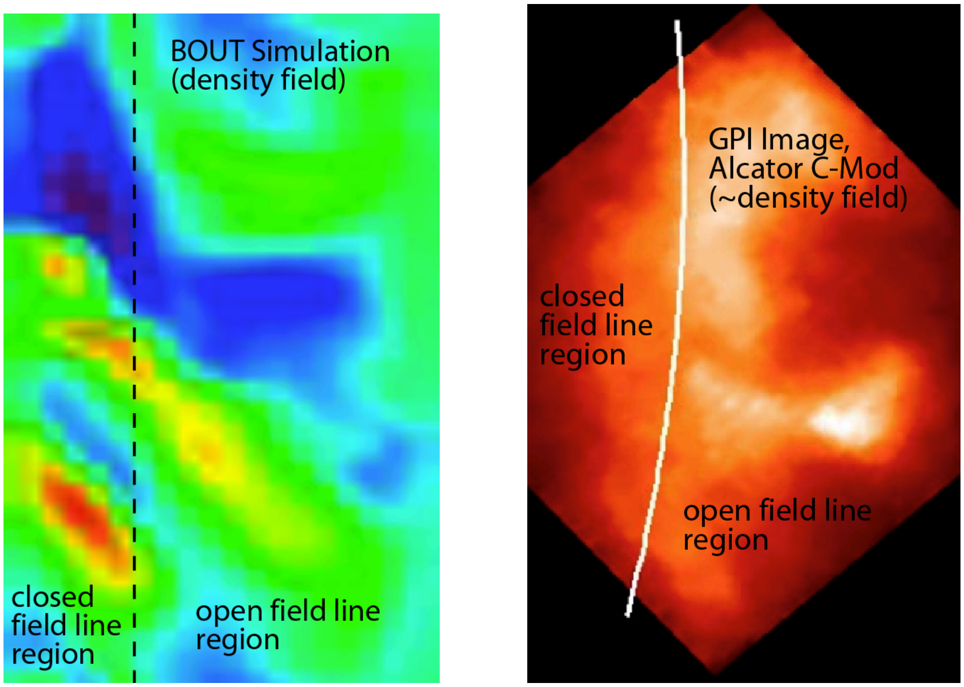

Fig. 2 – The physics associated with the transition from open to closed magnetic field lines plays a key role in edge plasma phenomenology. The plasma response changes from a drift-like transport behavior inside closed field line regions to an intermittent, 'blob'-like propagation behavior on open field lines, as simulated by the BOUT transport code [7] (left) and measured by gas-puff turbulence imaging on Alcator C-Mod [8] (right).

3. Measurements to be made

Computational models of the phenomena outlined above are slowly emerging but systematic comparison with experimental observations is at a relatively early stage. To address the important physics questions, two sets of data are essential – plasma profiles and fluctuations. Of interest are the profiles (n_e, T_e, ϕ_p, V_{perp}, $V_{parallel}$) in the SOL measured at several poloidal locations. To study turbulence directly, phase-resolved fluctuations of n_e, ϕ, T_e, B, V_{perp}, $V_{parallel}$ at various radial and poloidal locations will be required. Most of this data could be obtained with probes of various configurations, augmented with imaging diagnostics and a modest set of standard plasma core diagnostics. Analysis techniques would be spatiotemporal fluctuation analysis of various types including wavelets, conditional techniques and higher order spectral and chaotic methods. One notes that despite decades of work, interpretation of probe data is still quite challenging. Experiments designed to cross-check measurements from multiple diagnostics could lead to fundamental advances in this area and to ensure the data quality needed for validation studies. Resulting innovations and enhancements to synthetic diagnostics might be quite productive.

4. Modeling requirements and issues

Currently there are relatively few codes, even under development, which attempt to solve for plasma turbulence in the relevant geometry and parameter regimes. These include BOUT [9], TEMPEST[10], and XGC0,1 [11]. Fortunately, with the proposed experimental geometries more or less identical to those for which the codes were designed, it is likely that only minor modifications would be required. The improved diagnostic access would allow testing of 2D (and perhaps 3D) dependences that are quite challenging on high-performance devices. Coupling turbulence codes to models for atomic physics, neutral transport and radiation transport may be necessary for complete understanding and is largely an unmet challenge.

5. Connection to other devices

The physics of the boundary layer plasma in the proposed configuration could be expected to be quite similar to what is found in high-performance devices, but with greatly improved diagnostic access. Enhancements and extensions to these experiments might be achieved with auxiliary heating systems (ICRF, ECH), which could be used as tools to explore heat deposition profile and Ti/Te effects across the open/closed field line interface. With RF, it would experience additional phenomena and physics that need to be understood for example, sheath rectification of RF waves and convective cells. Overall, the boundary physics in the devices described here could be compared quite directly to codes developed for high-performance toroidal devices where dimensionless parameters and turbulence behavior will not be vastly different. It would be complementary to devices with simplified geometry (linear or toroidal without rotational transform), which would have a useful degree of physics overlap.

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Case study II. Validation of Particle Transport Models in Small Magnetic Confinement Devices with Controlled Fueling Sources

1. Physics questions to be addressed

Particle transport is one of the least understood processes in tokamaks. In an ignited reactor, the heat deposition profile will be determined by the alpha particle production rate and profile. Therefore, the only remaining actuator for control over the pressure profile in a reactor is the density profile, which is of course determined by fueling and particle transport. An understanding of particle transport is therefore critical if we wish to manipulate the pressure profile in a reactor.

In all existing experiments, particle fueling is dominated by recycling. The existence of a single, uncontrolled, edge-localized source makes the experimental investigation of particle transport difficult – we cannot control the largest source of particles in a typical tokamak. The degree to which the fueling profile would control the density profile, in the absence of an edge localized source, cannot be easily determined. Comparisons of particle transport models to experiments with controlled, core-localized fueling sources cannot be easily made at present.

This exercise would address the validation and verification of particle transport models under the following conditions:

1. A reduction or near-elimination of the edge particle source, with a low recycling wall.
2. Transient elimination of all particle sources, between gas fueling pulses.
3. Low electron and ion collisionality over the full plasma radius ($\upsilon_{i,e}^* \sim 0.01$). In addition, a low edge neutral population will reduce electron-neutral collisions.
4. Limited control over the core fueling profile.

The density profile in edge-fueled discharges can be compared to those dominated by core fueling, or by no fueling, to explore the degree to which marginal stability determines the density profile. Factors which cannot be significantly varied in a small device include the trapped particle fraction, and the moderate – large value of ρ^*, due to geometry restrictions.

2. Experimental configuration

Aside from the particle fueling profile, many factors can have a role in determining transport. These include the magnetic field geometry and shear, collisionality, ρ^*, and the trapped particle fraction. Transport is also affected by the edge conditions (H-mode vs. L-mode), although this may be related to the fact that edge fueling dominates in a tokamak with a recycling wall. An ideal experiment would provide control over all these conditions, and add a precisely controllable fueling source. It is difficult to imagine an experimental configuration that can fulfill all these requirements. However, the most fundamental requirement for an experiment to test particle transport is the ability to control the particle source profile. This can only be accomplished if the edge particle source can be eliminated, with a nonrecycling wall.

This case study develops validation work that could be carried out on any experiment that controls particle sources with a nonrecycling wall. A first test of operation with a fully nonrecycling wall will take place in the Lithium Tokamak eXperiment (LTX) at the Princeton Plasma Physics Lab. If LTX can successfully demonstrate operation with a liquid lithium thin film wall, and that such a wall can reduce recycling to the point where the wall particle source is negligible, then it should be possible to implement similar systems in a variety of small confinement experiments. The elimination of a neutral-dominated "edge" from small devices is an important consequence.

Metallic lithium has been shown to be an effective pump for hydrogen in test stand experiments [1] and on the predecessor to LTX, CDX-U [2]. Particle transport studies were an original physics goal of LTX. The remaining research goals for LTX [3] are not essential to a study of particle transport, although control over the electron temperature could remove important drive terms for instabilities such as the ETG.

LTX has been described elsewhere [3]. Here we only point out that the device is a modest pulse length (100 – 200 msec), low aspect ratio tokamak with R_0=40 cm, a=26 cm, B_{TF}<3.2 kG, Ip< 400 kA, with very modest neutral beam injection (P_{NBI}~100 kW~P_{Ohmic}). 85% of the last closed flux surface is covered by a conformal, heated, lithium coated wall which will be maintained at a temperature of ~300 °C, well above the melting point of lithium (180.5 °C). The wall is designed to reduce recycling to the irreducible level imposed by direct reflection (10 – 20%). It is certainly possible to envision installing such a wall in other experiments; LTX after all is an upgrade to the earlier CDX-U experiment.

Tools to perturb the density for particle transport include close-coupled gas sources such as a supersonic gas injector for edge-localized perturbations. A molecular cluster injector is expected to generate density perturbations at or within the plasma half-radius [4]. The neutral beam (5A, 20 kV), when installed in 2011, may provide enough of a core-localized source in the small plasma volume of LTX (0.8 m^3) to provide an observable particle source. If the confinement in LTX agrees with scaling from the CDX-U results, then the beam will provide up to 20% of the total required fueling. The neutral beam is designed to be modulated, so the beam particle source can be pulsed, and the evolution of the density profile can be documented following beam turn-on or turn-off. The ability of a modest neutral beam to significantly perturb the density in a small-volume plasma enables cost-effective core fueling studies in small devices.

The diagnostics for particle transport studies in LTX include a novel system, Digital Holography, which can diagnose fast perturbations in the density profile, and a two-channel (one fixed, one movable) interferometer system to obtain the baseline density profile. The time response of the digital holography system is sufficiently fast (up to 40 kHz, over a reduced view) and has sufficient resolution (down to 0.3 mm) to also inform the fluctuation spectrum. Thomson scattering is available for electron temperature profiles, and (proposed) Li-CHERS will be used to diagnose the ion temperature profile. Supplemental core density diagnostics (e.g. beam-emission spectroscopy (BES), or phase-contrast imaging, among others) are desirable to explore the full frequency and wavenumber range of density fluctuations, which preliminary simulations indicate will be f< 50kHz, and k of order 10 cm^{-1}. A similar ability to diagnose core density fluctuations is a requirement for any study of particle transport in a small device.

There are numerous limitations to performing this exercise on a small device. Linear devices generally employ limiters to define the plasma edge, and do not usually have a separatrix; similarly, LTX is wall-limited rather than diverted. This distinction may introduce differences in particle transport in the edge compared to a divertor tokamak. The diagnostics available on smaller devices are of course not as complete as on a large tokamak. Important diagnostics that are needed for this exercise include BES or a similar diagnostic of core density profiles, and Li-CHERS or a similar system for core ion temperatures. But the number of channels for these core -viewing, beam - based diagnostics will always be limited compared to larger devices. A diagnostic for the current profile would be highly desirable. In the case of LTX, the current profile can only be modeled from the magnetics data. The fueling systems available on small confinement devices, which can deliver sufficient particle input to sustain the plasma, also produce a significant particle source in the edge. Although this source is far smaller than recycling, or even conventional wall-localized gas puffing, it still represents a complication. Removal of this edge source requires pulsing the fueling systems, and studying the density profile evolution, and the density turbulence, transiently, between fueling pulses. Small devices are restricted to large ρ^* (of order 0.03 for LTX), if they are sufficiently hot to reduce the collisionality to values relevant to larger tokamaks. Small ρ^* can probably only be accessed at the expense of increased collisionality. And finally, LTX in particular is a low aspect ratio tokamak, with a large trapped particle fraction. The geometry cannot be changed in any small (or large) device, to any significant degree.

Neutral beam-based diagnostics, employing small (nonheating) neutral beams, can address most of the diagnostic limitations. In some cases (e. g. LTX) the beam may already be available. One of the more prominent features of divertor operation – a hot edge – may be replicated with nonrecycling walls, and of course divertor coils can be added, even in a linear machine. It is also possible that extending particle transport studies across a spectrum of small devices with nonrecycling walls can significantly expand the range of conditions investigated.

3. Measurements to be made

We summarize the measurements that will provide input for numerical modeling. The average plasma profiles (n_e, T_e, T_i) will be characterized, although T_i measurements require a modest increment in the program. High spatial, time resolution measurement of perturbed $n_e(r)$ (via digital holography), and the time-evolving density gradients, will be available. The density fluctuation spectrum in the core will be available from a combination of the digital holography system, and beam emission spectroscopy. The additional hardware requirements, over the baseline program, are the Li-CHERS and

BES diagnostics. Note that digital holography is a development project funded through a Phase II SBIR, rather than a mature diagnostic.

4. Modeling requirements and issues

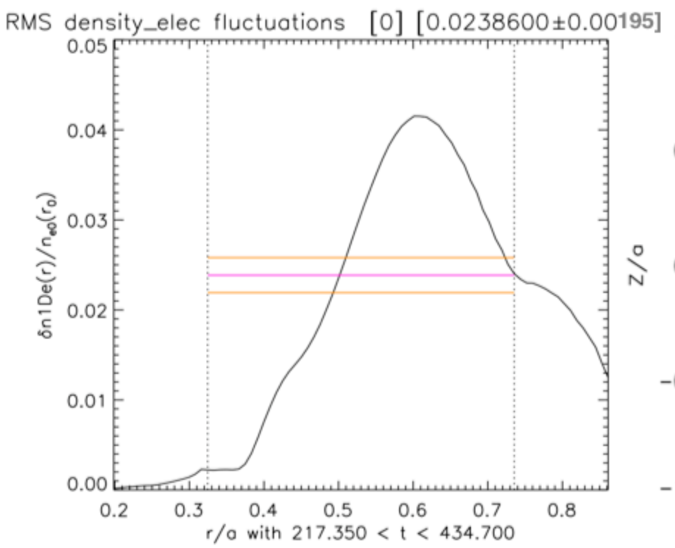

Figure 1. RMS density fluctuations as a function of normalized radius, predicted by the GYRO code, for LTX density and temperature profiles. The modeled profiles have been previously published [3].

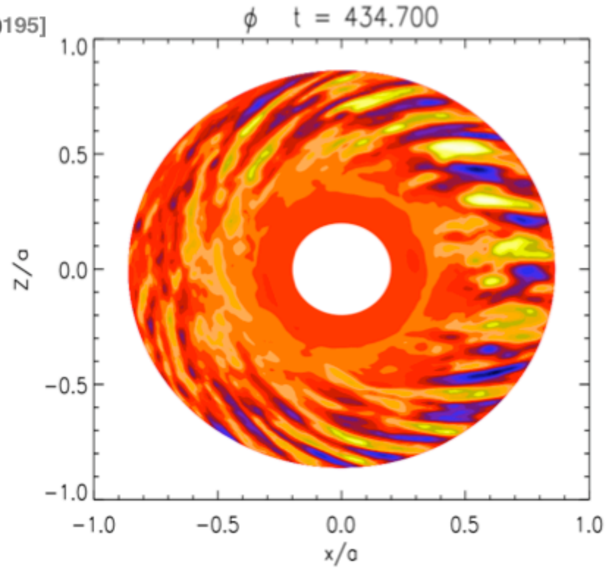

Figure 2. Cross section of LTX, indicating the radial and poloidal wavelength of density fluctuations predicted by GYRO. No instability is driven near the axis (white area).

The primary code we envision benchmarking is GYRO [5]. GYRO has already been used for preliminary modeling of LTX, using projected density and temperature profiles for the discharge. Preliminary GYRO modeling of LTX is shown in Figures 1 and 2.

This comparison of experimentally observed density fluctuations with simulations from the GYRO code will comprise part of the dissertation research of a Princeton University graduate student. Synthetic diagnostics will be installed in GYRO for this purpose. Comparisons will include observed and predicted power spectra and correlation lengths for drift wave turbulence, and a determination of whether drift wave turbulence is responsible for the observed transport. Comparisons of modeled and experimental observations of global confinement have also been made with the GLF23 code [6], for the CDX-U low recycling results [3], and comparisons with this numerical model are also underway for predicted LTX profiles.

The comparisons made so far, using modeled profiles, are very sensitive to the profiles of density and temperature, so accurate profile information will clearly be required. An example of a profile where good accuracy is required is the ion temperature profile, where the existence or nonexistence of the ITG mode strongly affects the predicted value of χ_i. The ion-heating tool provided by NBI, and Li-CHERS to diagnose the ion temperature gradient, are clearly important.

5. Connections to other devices

This experiment is specifically designed to represent a simplification of the configuration typically present in a high recycling tokamak, with an edge-dominated source. The general validation of drift-wave driven turbulence as modeled by GYRO, however, should have wide applicability. Except for the lack of an edge source, many other parameters of interest (e.g. collisionality) should be relevant to larger devices. A notable exception is ρ^*, which is significantly larger here than in any large tokamak. Certainly, experimental results from this exercise must be carefully compared to those obtained on larger devices.

It may be possible to undertake a similar study in a smaller device than LTX, or in a linear device. Note, however, that the premise here is that the edge particle source due to recycling is eliminated. In order to replace recycling with external fueling, a certain minimum level of particle confinement is required – or an impossibly large fueling source would be necessary. It is also possible that these studies can be extended to larger devices, such as NSTX or another large tokamak. This could extend these studies to lower ρ^*; this scaling opportunity would provide important further verification of GYRO or other particle transport codes.

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Case Study III. Linear and Nonlinear Dynamics of Edge-Localized MHD Modes

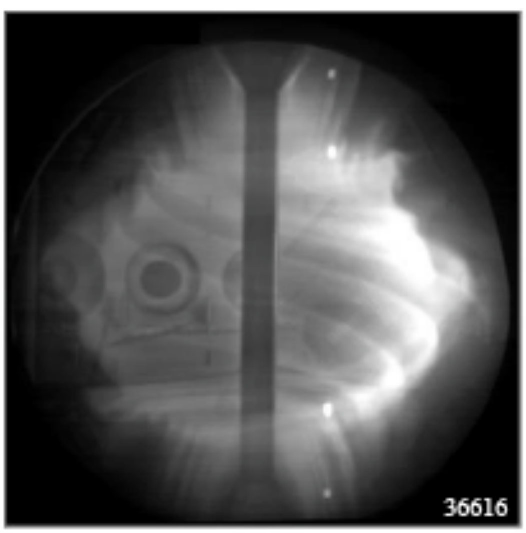
1. Physics to be addressed

The physics topics of interest are the linear and nonlinear properties of MHD instabilities localized to the edge region of magnetic confinement devices. The goal is to demonstrate predictive capabilities of all phases of the instability dynamics starting from initial linear growth to nonlinear evolution to saturation. While the linear phase is dominated by ideal MHD physics, nonlinear evolution processes are not well understood and may be determined by non-ideal MHD processes.

Edge MHD instability properties are of importance to the general tokamak community but of particular relevance to burning plasmas and ITER. The initiation of the edge localized mode (ELM) process is thought to correlate with the breaching of intermediate-n ideal MHD stability boundaries[1]. ELMs are nearly ubiquitous in H-mode tokamak operation. They produce periodic losses of particles and stored energy. Phenomenological scalings predict ITER will lose substantial fractions of the pedestal store energy with each ELM. While theoretical tool have been developed to predict the onset of ELMs, there is no widely accepted theoretical model for the nonlinear evolution.

2. Experimental configuration

The experimental configuration required for this work needs to routinely operate with edge localized MHD instabilities. Attractive options include spherical tokamaks that operate with low-l_i and large edge currents. Edge currents can drive intermediate-n peeling modes. The Pegasus ST at the University of Wisconsin is well suited for these studies.



Fast CCD camera images of Pegasus show a prominent filamentary structure at the tokamak periphery that is reminiscent of similar phenomena associated with the ELM phenomena of tokamak H-mode confinement[2]. Moreover, measurements have clearly demonstrated that these structures have a magnetic signal and the toroidal mode numbers of this phenomena are typically n ~ 3-5. The corresponding poloidal mode structure is peaked at $m \sim nq_a$ as expected for MHD instabilities.

By operating with broad current profiles ST's can routinely produce edge localized MHD instabilities. However, additional control tools for current (such as EBW), particle, heat and flow sources may be desirable to fully elucidate the physics. Another important element is the presence of a magnetic separatrix; (Pegasus does not presently operate in divertor geometry). While smaller devices do not operate at reactor relevant levels of ρ^*, spherical tokamaks typically operate at small ν^* due to their relatively short connection lengths.

3. Measurements to be made

Highly detailed measurements of the MHD equilibrium are required for comparisons to theory/computation. Of particular note is the measurement of edge localized current profiles. One advantage that smaller machines have over their higher performance counterparts is the ability to insert magnetic probes in the edge region for current profile determination. In larger tokamaks, edge current profiles are generally not directly measured, but rather inferred from magnetics and equilibrium reconstruction. Present activities on Pegasus currently employ edge magnetic probes as part of their activities to produce high fidelity equilibrium reconstructions.

Linear ideal MHD stability studies for edge-localized instabilities are highly sensitive to the details in the profiles. High fidelity edge temperature, density and current profiles are required where the precise resolution requirements need to be quantified with the input of theoretical modeling. An important question that needs to be addressed is how sensitive the nonlinear physics is to the precise details of the initial equilibrium. Further, a collection of fluctuation diagnostics is required to characterize the nonlinear dynamics. Guidance from theory/simulation is needed for precise specification.

4. Modeling requirements and issues

The ELITE code has been used with success in characterizing the linear onset phase for edge-localized instabilities[3]. However, ELITE has limited applicability. It is a linear code using ideal MHD equations. Two-fluid physics is known to adjust the linear onset conditions (ELITE only accounts for this physics in an approximate way). ELITE is incapable of predicting nonlinear consequences for breaching instability boundaries. An open theoretical question to address is why linear ideal MHD stability theory works as well as it does despite limited applicability. The answer to this question may have implications when results are scaled up to burning plasma/ITER conditions.

Nonlinear extended MHD codes such as M3D or NIMROD are uniquely qualified to provide the required modeling the nonlinear physics. Both codes have the demonstrated the ability to simulate nonlinear edge MHD instability dynamics[4,5]. Additionally, both codes are capable of describing both the realistic geometry of Pegasus and actual parameters of the experimental operation. At the moment, there has been little direct comparison between the extended MHD codes and experiments on the topic of edge-localized instabilities.

The extended MHD codes have been successfully benchmarked with ELITE with regards to predicting the linear onset conditions and linear growth rate spectra[6]. Nonlinear simulations of edge localized MHD mode activity using resistive MHD models have been performed on both M3D and NIMROD. Nonlinear two-fluid simulations are in the early stages, but are expected to become more routine in the coming years.

5. Connections to other devices

Growth of edge localized MHD instabilities are commonly associated the ELM phenomenology of H-mode confinement. Nearly every large tokamak in the international community has documented this behavior and produces an extensive characterization of ELM properties. A small ST can arguably provide the strongest test of peeling mode linear stability validation with detailed edge current profile measurement. This validation will improve our confidence in companion studies of linear edge localized instability studies carried out on other devices.

If predictive capability for characterizing the nonlinear evolution of edge localized instabilities can be demonstrated, it may have a profound impact on the future of burning tokamaks, ITER and DEMO. The nonlinear simulation tools can be used with greater confidence to provide input into the development of methods to combat the deleterious effects of ELMS.

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Case Study IV. Validation of Edge Turbulence Codes via Studies of Turbulence Dynamics in Laboratory Experiments

1. Physics Questions to be Addressed

The edge region of confinement devices is critically important, having a direct impact on the ultimate performance of a fusion reactor. The edge is a complicated region, with strong gradients in plasma parameters, including collisionality, a transition from closed to open field lines and interaction with neutrals and material boundaries. The development of a predictive capability for the plasma edge ultimately requires the integration of all of these physical effects, which might interact in a non-trivial way, into a simulation code in relevant geometry. However, when possible, it is valuable to isolate physical phenomena in order to develop basic understanding and validate simplified predictions from simulation. A validation effort linking edge turbulence codes to a variety of open-field-line laboratory experiments (linear devices, simple toroidal plasmas) is proposed. Edge codes which are built to deal with cooler, more collisional plasma and boundary effects (open field lines, sheath boundary conditions) are very important and could be tested using these simple experiments. Such an effort will build on a strong foundation of laboratory work in the area of instabilities, turbulence and transport [add citations here] and can make use of existing experimental programs. The focus of this validation effort would include:

(1) Can we reliably predict characteristics of measured turbulence such as ω-k spectrum, profiles, correlation length and time, particle flux, and coherent structure (blob) generation? A range of experiments exist with unique fluctuation characteristics to test the codes over a wide range of scenarios, e.g. experiments with fully developed turbulence and others with coherent modes that can study the transition to the turbulent state. The role of neutrals, atomic physics, and sheath boundary conditions would be explored.

(2) Do we fully understand flow generation and flow-turbulence interaction in simple plasmas? Compare simulations of turbulence-generated flows with measurements, including detailed turbulence measurements (e.g. Reynolds stress and momentum transport). Compare to experiments with external flow control (e.g. biasing). Determine the importance of non-turbulent flow generation in open-field-line systems, e.g. due to boundary/sheath-driven potentials.

A successful validation program would involve a significant increase in effort to compare to state-of-the-art simulation codes and models (e.g. sheath models) as well as a stronger coordination between experiments.

2. Experimental Configuration

The effort could include both linear and simple toroidal devices, enabling a comparative study of the effects of geometry. A number of existing experiments could be utilized in a coordinated study, including: simple toroidal devices such as the UT Austin Helimak [1], the TORPEX device [2] and linear devices such as the Columbia Linear Machine (CLM) [3], HelCat at UNM [4], CSDX at UCSD [5], and LAPD at UCLA [6]. These devices have a range of ionization fractions, species mixes, etc. The variety of sources in these devices (e.g. cathode, RF, arc) might also be useful in investigating possible source effects (e.g. current-carrying vs. current-free). It may also be possible to realize a laboratory device that could be constructed to investigate effects of specific magnetic geometries, such as the X-point region.

The existing set of low temperature devices has well diagnosed plasmas, including profiles, fluctuations, fluxes, and flows. Some measure of control of profiles (density, flow) is possible, for example using biased electrodes. A range of experiments could be utilized with unique fluctuation characteristics to test the codes (e.g. experiments with fully developed turbulence and others with coherent modes that can study the transition to the turbulent state). In modeling of fusion plasma edges, it is critical to get boundary conditions right on open field lines, and basic laboratory devices help simplify and isolate the effect of material boundary for comparison to simulation prediction; e.g. the importance of the sheath BC in blob charging

Limitations in this type of devices include poor confinement, limiting the accessible range of temperature and collisionality. Only in large devices can perpendicular transport compete with parallel losses in establishing plasma profiles (e.g., this is the case in LAPD). The plasma sources used in these devices typically result in primary electron heating and therefore very low ratios of ion to electron temperature. Direct ion heating, such as the RF scheme utilized in CLM [3] could be used to overcome this limitation. Due to limitations on plasma size and magnetic field, ρ_* can be large in basic laboratory devices. However, a range of different ρ_* values is possible across different devices, ranging down to $5x10^{-3}$ for a device like LAPD. Open field lines in these devices results in parallel boundary conditions playing a potentially important role in turbulence and flow dynamics. The boundary conditions must be well characterized experimentally and simulations must account for parallel boundary effects, including sheaths and neutral effects. Neutrals can be essential in the dynamics of these experiments, through, e.g. flow damping, instability drive, and providing conductivity for cross-field currents. Control and diagnosis of neutrals is difficult, but is possible in these devices. Furthermore, the role of neutrals can be understood through comparison between devices with differing ionization fraction. Though it may not be possible to get around all limitations in a *single* device, utilization of a variety of linear and toroidal devices that each have somewhat *different* limitations will help elucidate and overcome the restrictions of each.

3. Measurements to be Made

Measurements would include as complete a set as possible of plasma profile (density, temperature, flow, potential), fluctuations, and flux of heat, particles and momentum. Diagnostics would include probes, imaging (e.g. fast framing cameras for turbulence imaging), microwave diagnostics (interferometry) and passive and active spectroscopy (e.g. LIF for flows and ion distribution function). Neutral profiles are also likely to be very important. This seems obvious in the devices with relatively low ionization fraction, but effects such as neutral pile-up at the edge (hollow neutral profiles) may make understanding of neutral profiles critical in all of these experiments. Also, in some devices, such as LAPD, neutral collisions are not as important in linear resistive drift wave (Coulomb collisions are much faster) but play a role in flow damping and cross-field conductivity [7]. Neutrals are typically poorly diagnosed in these devices, and significant effort in developing and improving neutral profile measurements may be needed.

4. Modeling Requirements and Issues

Both fluid and kinetic codes are relevant, but clearly both need to include collisional and neutral effects and possibly atomic physics. The effort would start with existing fluid codes such as the Boundary Turbulence code (BOUT) [8]. Future codes (e.g. edge kinetic simulation) could be built around an incremental validation effort, starting with validation of core physics of simulation in simple geometries, for example.

Significant modifications are potentially required to adapt existing toroidal codes to linear geometry. For example, adapting to boundary conditions in linear devices and removing curvature terms can be nontrivial. Some examples of such modifications already exist, which are now being actively utilized in code-experiment comparisons, including the LLNL BOUT code applied to LAPD, the 3D Braginskii code of Rogers and Ricci applied to TORPEX and the Helimak [9], and comparisons between fluid simulations of Naulin and linear devices such as VINETA [10].

5. Connections to Other Devices, Including High Performance Devices

At its core, the fundamental nonlinear physics of turbulence, including its interaction between multiple modes, flow profiles, neutrals, sheaths, and boundaries, appears to be common to a large degree to large fusion devices, smaller toroidal devices, and laboratory experiments. Differences exist, no doubt, due to magnetic geometry, collisionality, specific modes involved, etc. But the apparent underlying commonality would seem to make such a validation effort highly complementary to large, high performance fusion devices. Utilization of the wide range of devices above would inherently allow for a range of different physical effects to be tested in both models and experiments. A detailed understanding of the plasma edge is critical in magnetic fusion for understanding dominant particle and energy sources/sinks, wall/divertor loading, etc. Validated physics models of this region would have a major impact on understanding and design of current and future fusion devices.

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Case study V. Validation of RF Sheath Models

1. Physics questions to be addressed

Energetic sheaths created through RF rectification can damage plasma facing components (PFCs) and cause impurity generation. Experimental evidence for radio frequency (RF) amplification of ambient initial Bohm few eV sheaths to a few hundred eV on plasma facing components (PFC) has been observed in fusion experiments such as JET, TFTR, Alcator C-Mod, Asdex-Upgrade, and Tore-Supra [1]. We propose to investigate the so-called hybrid sheath effect in which coherent RF waves along the field lines travel some distance of several meters to a PFC and non-linearly couple energy to the existing thermal sheath possibly raising the sheath potential from a few eV to above the sputtering potential and cause impurity generation. Although efforts are underway to better diagnose these effects on existing tokamaks, plasma temperatures and vessel access limit what can be done. In order to rigorously test the theoretical predictions and experimental dependencies we propose using a basic laboratory experiment with simple magnetic geometry. Such an experiment would need to support propagation of fast and slow magnetosonic waves and allow detailed measurements of wave fields and sheath potentials. An existing facility that could be used for such a validation effort is the Large Plasma Device (LAPD) at UCLA. This case study will use LAPD as an example to develop a more specific plan for a validation study. Possible parametric studies would involve: field line length, angle of the field line with respect to the PFC as well as to the launching structure, RF power coupled to the slow RF wave — flexible access in LAPD will facilitate adjustments to the experiment as studies progress. The primary measurements would be of the rectified potential at the sheath and of the rf fields in the plasma between the sheath and antenna. LAPD has existing embedded probe capabilites to measure both the rf potentials in three dimensions and the sheath potential. By comparing to basic theory we can validate and then apply it with confidence to fusion devices. Quantitative comparisons can be done with a two dimensional finite element implementation of the theory that is underdevelopment at MIT in collaboration with Lodestar under the RF-SciDAC. This should result in the most rigorous testing of this phenomena and associated theory to date.

2. Experimental configuration

The LAPD device at UCLA is a long cylindrical plasma device with an externally imposed axial magnetic field with length L=18 m, diameter D=60 cm, density $n_{e0}=5\times10^{12}$ cm^{-3} , electron temperature 0.025 eV $<T_e <$ 10eV, and magnetic field 50G$<B_z<$2.5kG, and ion temperature $T_i\sim$1ev, with a plasma composition of H, He, Ar, Ne, Xe in any combination. Higher temperatures may be possible with future high emissive cathode installation. Shear waves have been studied in detail, and an effort has begun to focus on the properties of fast waves in LAPD. The LAPD group is already pursuing development of an ICRF antenna that can be moved to several ports and adjusted to launch slow or fast Alfvén waves. A strike plate can be installed down stream from the antenna to have RF-sheath interaction at a specific surface with a specific composition.

LAPD has extremely flexible access and a simple physical and magnetic geometry. It can be operated at a range of density and RF parameters to allow various physical scenarios to be tested. LAPD has the capability to insert a target plate at variable distances from the antenna, and to tilt the plate at an arbitrary angle to the B field. This is very useful, as the sheath potential is a sensitive function of this angle. LAPD also has the ability to rotate the antenna, allowing slow wave launch. Limitations on antenna power may not permit the creation of sheath potentials of the strength found in tokamak experiments. The magnetic field strength will be lower as well. The expectation is that the experimental range available in LAPD will be sufficient to test the rf-sheath theory and codes to an extent that will justify their application to tokamak fusion plasmas. Planned upgrades in power sources will aid in the creation and detection of sheaths.

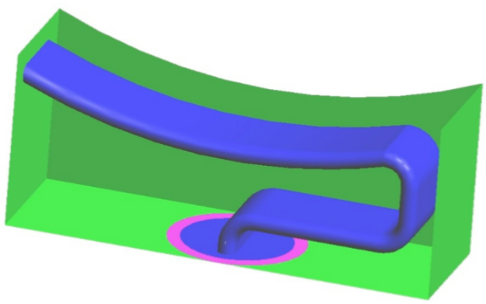

Fig1. Proposed antenna. Copper inside a copper box with glass shielding. The antenna is shaped with a 40 cm radius. The antenna will run at 1-2 MHz in He, H (minority) plasma. F = 2-10 fci. (He). Initial test will be at approx 1 kW. The antenna can be moved radially into vacuum or directly into the plasma. Design includes a Faraday shield.

3. Measurements to be made

Relavant rf scenarios would be: a) antenna drives *propagating SW*; sheath forms on plate normal to magnetic field, **B**, b) antenna drives *propagating FW*; sheath forms on tilted plate (not normal to **B**), c) *evanescent SW* driven by antenna; sheath forms on plate. The measurements needed to address physics or modeling issues include: measurements of electric potential at the strike plate, measurements of potential at antenna, and measurements of the rf fields in the plasma. Existing probes should be sufficient and LAPD experience includes the measurements of 3D rf fields and sheath potentials.

4. Modeling requirements and issues

RF sheath theory predicts a non-linear relationship between Child-Langmuir sheath potential and the RF fields [2,3]. Where the sheath-width, Δ_s, is the usual Child-Langmuir sheath width that is non-linearly related to the sheath potential. This is shown in the following equation:

$$E_t^{(\mathrm{sh})} = E_t^{(\mathrm{pl})} = \nabla_t\left(\frac{\Delta_s}{\varepsilon_0} D_n^{(\mathrm{pl})}\right), \quad \varepsilon_{sh} \approx \varepsilon_0 D = \varepsilon \cdot E .$$

The tangential displacement field is continuous along the sheath boundary. This leads to a non-linear boundary condition at the sheath surface between the plasma tangential electric field and the plasma normal electric displacement field.

A two dimensional finite element plasma wave code has been developed [4] that implements the Lodestar non-linear sheath boundary condition. It has flexible specification of the antenna alignment and the equilibrium field direction. It should be very suitable for applications to the LAPD device/geometry.

The code has presently been applied to slab geometries. The effects of cylindrical geometry would have to be added. Eventually extensions to three dimensions using a poloidal mode decomposition may be desirable. At first a single antenna poloidal mode would be used.

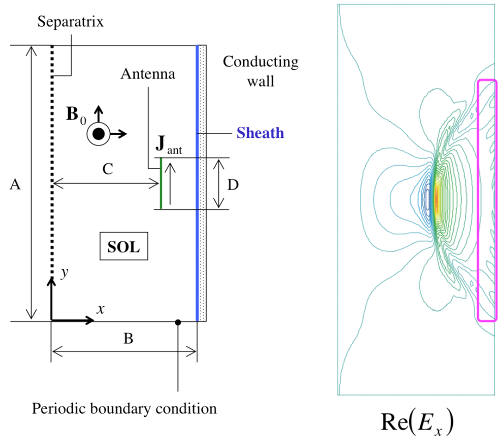

Fig 2. A simple slab geometry with finite B_{0x},B_{0y} used in the code is shown on the far left. The antenna angle and position are adjustable. To the immediate left, a component of the electric field calculated by the code is shown. The purple box indicated the area of the sheath.

Validation of RF sheath theory and its implementation in this code would increase confindence in the application of it to tokamak geometries where detailed measurements are more difficult to make. Predications of whether sputtering at PFCs would be expected could be made based on geometries and antenna power.

5. Connections to other devices, including high performance devices

The cylindrical geometry under study has similarities to the edge region in tokamaks where slow waves propagate. Higher antenna power may permit ablation and impurity studies. Power density at the strike plate could also be increased by moving it closer to the antenna.

A quantitative validation of existing theory and modeling will permit an extension of the modelling efforts to tokamak geometries with confidence. The ability to estimate the sensitivity of RF power lost in the sheath to experimental parameters will enable large fusion devices to determine accurate margins of operation to avoid PFC damage and impurity injection from RF sheath rectification effects. Understanding these effects is essential to making quantitative estimates for ITER, where even the vacuum field rf sheath model predicts extremely large antenna sheath voltages.[5, 6]

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Case Study VI. Validating Fundamental Mechanisms of Turbulent Transport in Multiple Channels

1. Physics questions to be addressed

Much of our transport modeling for future devises such as ITER is based on the assumption that we understand ITG turbulence from the linear phase to the saturated state, and the turbulent transport that it causes. It is however an open question as to whether our confidence is justified or misplaced. Even in the simplest transport channel (namely ion thermal transport), validating ITG models against experimental results has been difficult. The other channels - electron thermal, particle, and momentum – are not well understood. This case study envisions a well-designed set of experiments to address the details of the transport in each of these channels while controlling the instability to allow high-level comparisons with models and even fundamental theory. The types of experiments, and the questions that can be addressed fall into a natural progression of complexity and difficulty (both experimental and computational), which we lay out as three sets of questions. These questions are formulated so that they can guide validation, not just of comprehensive gyrokinetic models of ITG physics, but of reduced models that attempt to capture essential physics while limiting the description of nonessential effects.

The first set of questions addresses basic transport relationships. Given a mechanism (ITG or ETG for example): What are the properties of the transport in the different channels (ion thermal, electron thermal, particle, momentum)? How are they related? Which of them do the codes get right and which wrong?

The second set of questions addresses some of the fundamental characteristics of transport, such as whether the transport is diffusive or non-diffusive, etc. These are open scientific questions in their own right. For a particular transport mechanism under consideration the following questions would be investigated: What are the characteristics of the transport as a function of proximity to marginality, both above and below the marginal stability threshold? How electron and ion thermal transport, particle transport and momentum transport behave and change. Are they diffusive or non-diffusive, intermittent or continuous? What characteristics are needed in the codes to capture this behavior (fixed profile vs. fixed flux, etc)?

The third set of questions, clearly the most difficult, addresses the dynamics of multi-mode transport. When we combine two instabilities, ITG and ETG for example: What are the net properties of the transport in the different channels (again, ion thermal, electron thermal, particle, momentum)? How are they related and how does a change in one affect the other? Do the codes that treat multiple modes get this right?

2. Experimental configuration

The most important consideration for such a set of experiments is that the configuration be simple (either linear or a simple toroidal device), with profile control for all of the relevant quantities. To investigate all the transport channels, the profiles of temperature (both ion and electron for the full set of experiments), density and momentum, need to be controllable at least perturbatively. The ability to manipulate profiles so that a single instability is the only active (or at least very dominant) instability is critical. Clearly one needs the ability to control the profile, which is the free energy source for the instability in order to scan proximity to marginality, without exciting other instabilities. The configuration would need to be stable enough to get into a fully developed turbulent state, well beyond both the linear growth phase and the coherent or quasi-coherent states. An appropriate device or class of devises would probably be one that has a low enough temperature for good probe access through most of the cross section to allow adequate diagnostic access/coverage (this has the added advantage of allowing for a reasonable number of ion gyroradii across the radius).

This type of device has a number of advantages. Because the temperature is low the plasma can be well diagnosed. The device is designed to enable simple separation of effects. Similarly additional effects and transport mechanisms to be easily added, e.g. flows.

Some of these characteristics lead to limitations. The plasma is cool, simple, and the geometry may be linear, requiring that codes be modified and qualified for this operational regime. There are other potential issues that need to be investigated and addressed: 1) Can we get a steady state in a cool plasma with these instabilities? Is there enough of a "core" so one can ignore complicated edge physics? Are there enough ion gyroradii across the devise so one is out of the ballistic transport regime? Can the parallel transport loses be dealt with sufficiently so one can properly explore the turbulent transport?

3. Measurements to be made

At the first level, the ability to directly measure fluxes in each of the channels is needed. Profiles in each of the quantities of interest must also be measured. For appropriate validation, additional measurements of the lower level quantities on the primacy hierarchy, such as fluctuation characteristics, would be critical. For a linear device, one would need a way to quantify parallel transport, perhaps through perturbative experiments. To accomplish these goals, flux, profile and fluctuation diagnostics are needed. For a linear device, one would need a diagnostic to measure to parallel transport for perturbative experiments. Finally, to best capture the transport characteristics, it would be very useful to develop Lagrangian transport measurements. This would allow the most rigorous comparison to the models.

The analysis and comparisons would be made across the entire primacy hierarchy, and would be used to construct validation metrics for each of the codes and sets of experiments. The metric would be developed using tools from basic statistics, such as the mean, pdfs, and quantile-quantile analysis. These would extend all the way through dynamic measures such as spectra, higher order spectral techniques, correlation functions and structure functions.

4. Modeling requirements and issues

Many codes purport to capture the physics of ITG or ETG turbulence and turbulent transport. In principle, all the fluid and gyro-kinetic codes (GYRO, GTC etc) qualified for ITG conditions would allow for multiple transport channels. A hierarchy of codes from simple to complex (and including analytic calculations) could be used. However once again there are a few potential issues.

Code qualifications would need to be checked. If device is linear, as is likely, geometry will need to be changed for many of these codes and parallel loses will need to be added. It may be possible to deal with the parallel transport in the codes in an ad hoc way based on actual measurements in the experiment.

5. Connections to other devices, including high performance devices

While we expect that the transport physics studied in this class of devices would be broadly valid, connections to other regimes are important. This type of experiment therefore has natural connections to both higher performance devices and simpler machines. Dedicated studies in big devices and mined data from these experiments would be complementary and would allow the exploration of the regime of validity for the models. Similarly, code validation on smaller machines with coherent fluctuation dynamics would also be complementary and would exercise the models in another important regime.

If the device is made flexible enough, it could be used for further exploration of some important outstanding transport physics issues. These include the ability to explore the effect of flows, sheared flows and the impact of size (done through a rho-star scan) on all of the transport issues already discussed.

It is extremely important to know if our understanding of transport for the main presumed turbulent instability is a) correct at even the basic ion thermal level and b) for all of the other channels. Our modeling ability (and any predictive capabilities) for fusion devices is largely unknown without such an exercise.