A Hierarchal Approach to Validation Experiments in Magnetic Fusion Science

Validation Experiments Working Group

US Transport Task Force

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Predictive capability for complex fusion plasmas requires rigorous validation effort

Predictive capability sought, promised for operation of ITER, Demo

- How do you get it?
- How do you know when you have it?

From CFD:
Verification - Code faithfully represents a model
Validation - Model faithfully represents physical reality

Fusion plasmas present additional challenges for validation

- Usual intrinsic nonlinearity and multiple scales - *but in addition*
- No single model describes everything
  - Different models, different approximations, different physics
- Multiple equilibria with bifurcations
- Extreme sensitivity
- Serious limitations in measurement capability

Validation is rigorous application of scientific method to highly complex, nonlinear systems whose models require numerical solutions

We have always done validation at some level, but making modeling predictive requires new level of rigor, new approaches

Challenges

Fortuitous agreement - is purported agreement real?

Discriminating between models - for some measures, models with critically different physics may both compare well

Sensitivity - model may never agree well in sensitive measures

Optimizing comparisons - sensitivity vs. discrimination confronting measurement limitations

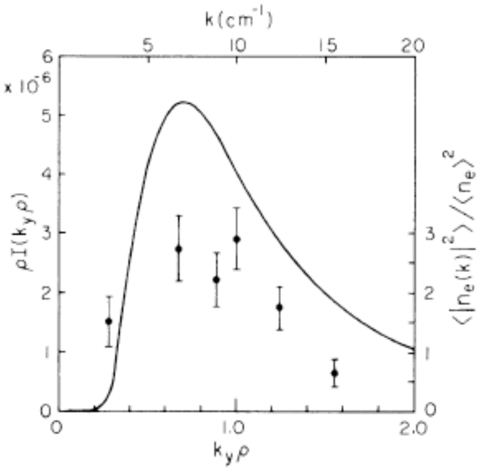
New validation approaches for fusion needed

Hierarchy of validation experiments

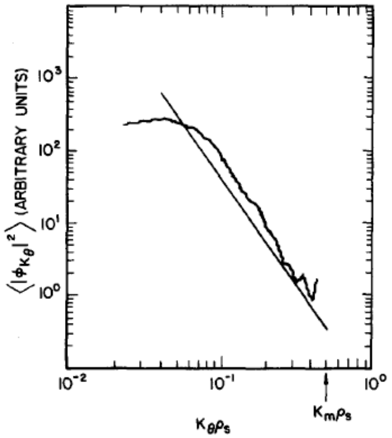
Detail from previous slide: fortuitous agreement and measures with poor discrimination are longstanding problems

Historically: *k* spectrum agreement easier to get than other quantities

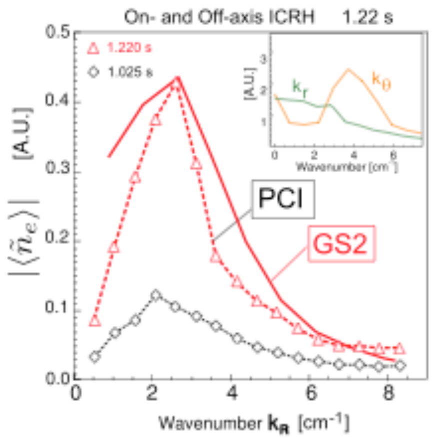
1976 ATC/theory



1985 PRETEXT/theory



2006 CMod/GS2



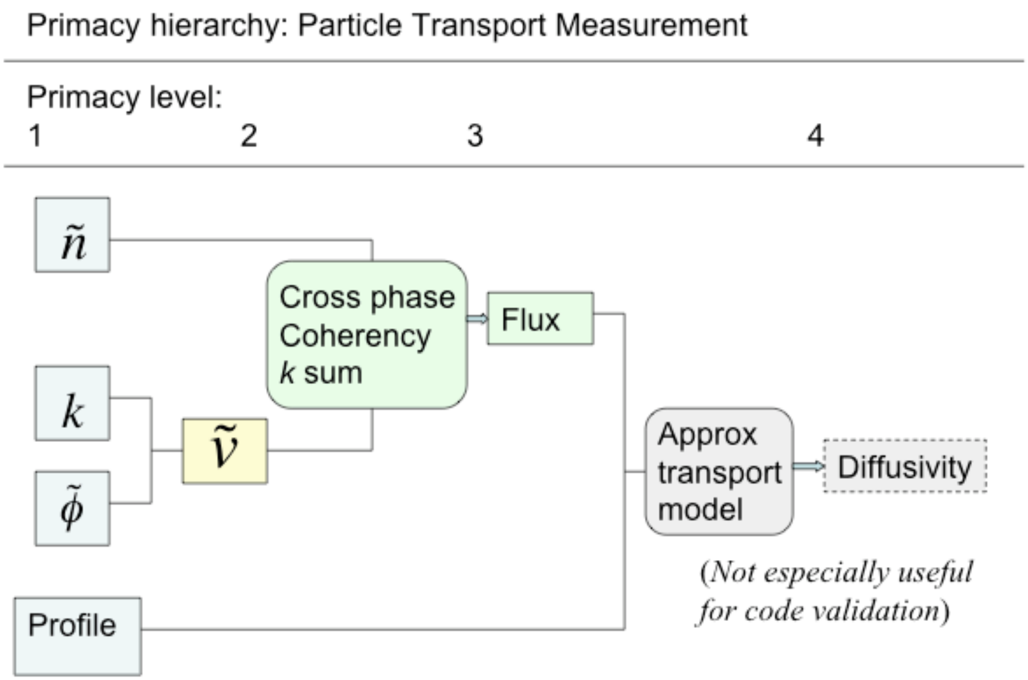
Increasing model complexity, analysis sophistication →

We might boldly say we have finally got it right

But with 10 B$ machine with 20 year develop/construction time riding on predictions, how confident are we?

Example of new validation approach: primacy hierarchy

Ranking of measured quantities by extent to which other effects integrate to set value of quantity (lower level - fewer effects integrated)



Measurements at multiple levels recommended – discrepancy between model and experiment generally varies with primacy level

Measurement at multiple levels unfolds complexity in measurement

Complexity in physics unfolded with hierarchy of validation experiments

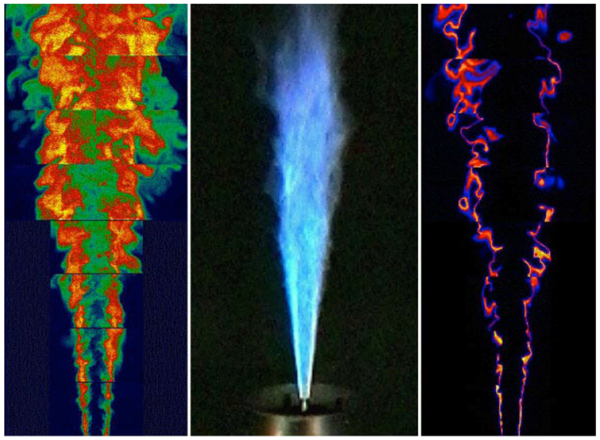
Example from computational fluid dynamics – turbulent nonpremixed flames:

Goal: reduce emissions in combustion engines

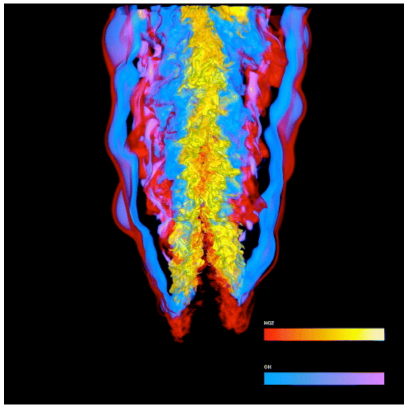
Validation of models using stand-alone flame experiments

- Remove boundary surfaces
- Remove complex geometries
- Better diagnostic access
- Better control
- Focus on turbulent chemistry in modeling
- Establish fidelity of inner workings of models

Restore complicating elements as validation and understanding achieved in simpler configurations



Flame, from various diagnostics



From numerical modeling

Hierarchy of validation experiments desirable for fusion

Predictive capability: assurance inner workings of models are right

Significant progress would be achieved with experiments that:

- Simplify geometry/magnetic topology
- Freeze quantities that vary in general
- Have key parameters in regime of simpler physics
- Integrate fewer disparate effects
- Allow enhanced diagnostic access

Such experiments would be valuable for training students

Problem: simplifications can change physics in fundamental ways

- Simpler geometry → degraded confinement → cold ions, neutral effects
- Simpler topologies → line tying, sheaths, change in connection length properties
- Scale reduction → different parameter values (ρ_*) lead to different physics

Limitations must be dealt with in experimental design

- Make unwanted effect less critical
- Treat limitations sequentially across more than one experiment
- Focus on validation measures that are less sensitive to unwanted effect

Validation Experiments Working Group: Can meaningful “simplified” validation experiments be created?

Case studies for experiments

- Range from existing devices to devices that could be built
- Not a comprehensive survey, just a sampling

In context of specific type of geometry, plasma parameters, etc.

- •Kind of physics questions addressed
- •Advantages to be gained in validation
- •How to deal with particular limitations
- •Measurements that would be made
- •Modeling requirements
- •How work would connect to modeling of high performance plasmas

Did not develop detailed proposals or work out every issue

Case studies argue for fundamentally new approach

Validation tasks envisioned from conception of experiment

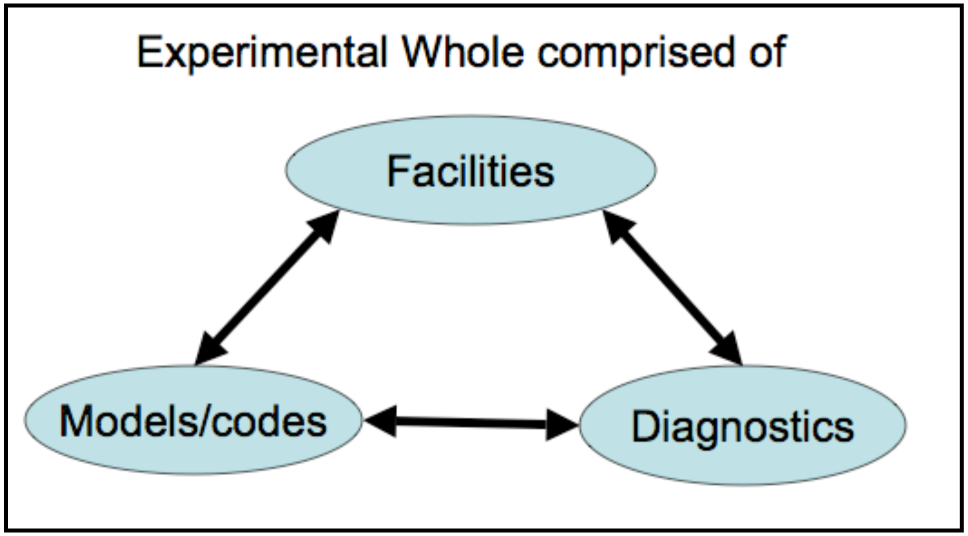
- Integral part of design
- Tied to physics understanding sought from experiment

Experiment must have diagnostics appropriate to validation mission

- Integral to experiment, not relegated to upgrade

Models integral part of experimental design

- Must match experiment
- Integral to validation mission


Experimental Whole comprised of

Facilities

Models/codes

Diagnostics

Validation approach must also advance considerably from past practice

- Validation at new level of detail, rigor
  - Characterize primacy hierarchy and measure across it
  - Understand sensitivities and properly treat in validation
  - Develop and use meaningful validation metrics
  - Develop new validation approaches
- Models are developed for specifics of experiment
  - Must be fully qualified
  - Code development may require *multiple man-year effort*
  - Where possible, use elements in comprehensive models
- Ideas must be developed for integrating with other validation work

Case Studies

1. Validation of boundary plasma models on a small toroidal confinement device
2. Validation of particle transport models in small magnetic confinement devices with controlled fueling sources
3. Validation of models for linear and nonlinear dynamics of edge-localized MHD modes
4. Validation of edge turbulence models via studies of turbulence dynamics in laboratory experiments with open field lines
5. Validation of RF sheath models
6. Validating fundamental mechanisms of turbulent transport in multiple channels

Case Study 1: Validation of boundary plasma models on a small toroidal confinement device

Physics:

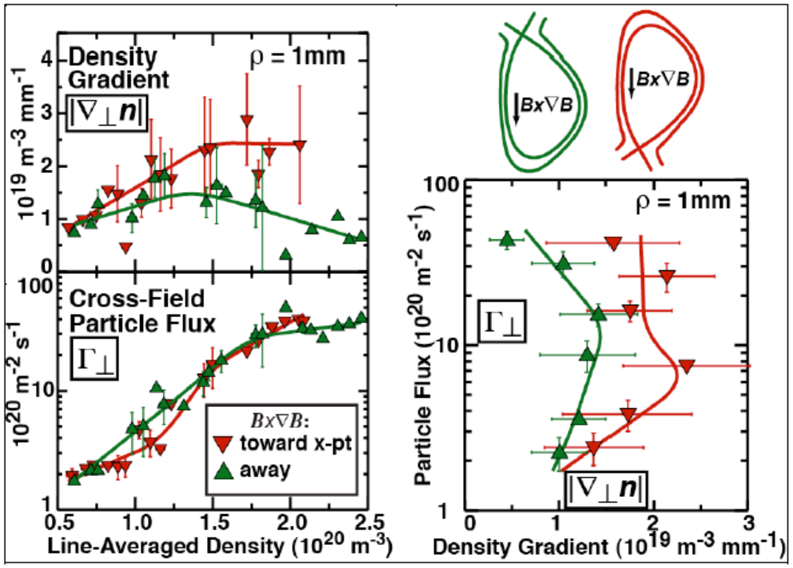
- Understand edge environment: profiles (SOL, separatrix), E_r, $v_{||}$, magnetic shear

Configuration:

- Toroidal – diverted tokamak or stellarator
- Low T, n for probe access
- Relevant geometry, topology, ||/⊥ scale length ratios

Limitations:

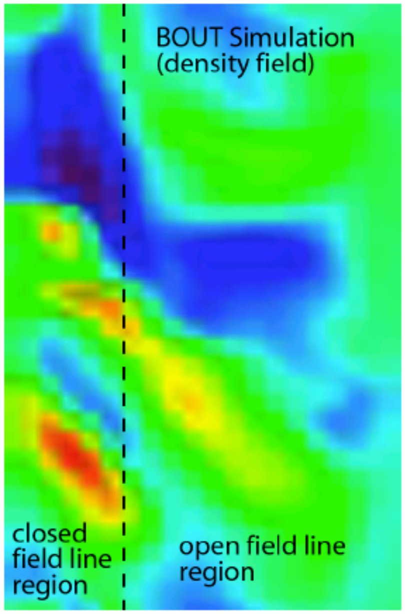
- Neutral interactions: stronger in core, weaker in SOL
- Short pulse length (tokamak) or different flow, particle loss characteristics (stellarator)

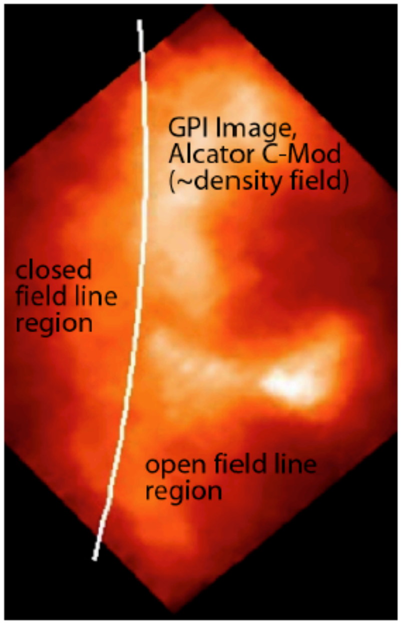


To mitigate limitations:

- Pumping, wall conditioning to limit neutral effects
- Increase R/a, transformer, rep. rate to compensate for discharge time
- Quasi-symmetry for stellarator

Case Study 1: Validation of boundary plasma models on a small toroidal confinement device





Measurements:

- Fluctuations and profiles in n, ϕ, T, B, $v_{\perp}$, $v_{||}$ various places r, θ
- From probes, imaging, standard core diagnostics

Modeling:

- BOUT, TEMPEST, XGC0,1 readily adaptable
- Improved diagnostics: test 2D, 3D dependencies
- May need to model atomic physics, neutral transport, radiation physics

Connection to other devices:

- Similar to high performance devices, bridge to linear devices studying edge physics (Case study 4)

Case Study 2: Validation of particle transport models in small magnetic confinement devices with controlled fueling sources

Physics:

- Particle transport in plasma with wall recycling particle source removed
- Vary fueling (edge/core/none): study role of marginal stability on density profile

Configuration:

- Any device that controls particle sources with nonrecycling wall
- LTX is example of toroidal device with liquid lithium thin film wall, modest pulse length, low aspect ratio, modest neutral beam power

Limitations:

- Small devices: Fewer channels for core diagnostics, edge fueling, large ρ_*, aspect ratio inflexible

To mitigate limitations:

- Pulse fueling, study particle transport between pulses; lower ρ_* at expense of increased collisionality; use multiple devices to vary geometry (R/a)

Case Study 2: Validation of particle transport models in small magnetic confinement devices with controlled fueling sources

Measurements:

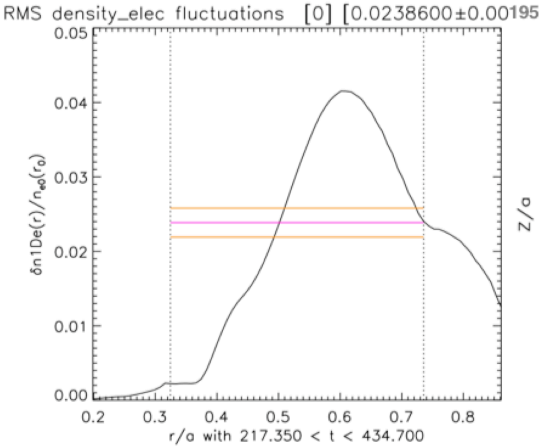
- Profiles in n_e, T_e, T_i
- Fast time variation of n, dn/dr
- fluctuations of n, T (for off diagonal transport)

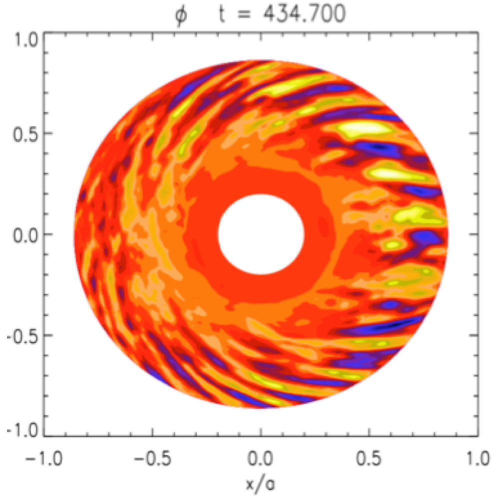
Modeling:

- Gyrokinetics. Landau fluid models
- Sensitivity to profiles is key issue
- Ion heating via NBI, T_i measurement crucial for determining whether ITG plays role

Connection to other devices:

- Many similar parameters to high performance devices
- Non recycling walls could be applied to linear machines





Case Study 3. Validation of models for linear and nonlinear dynamics of edge-localized MHD modes

Physics:

- Linear and nonlinear properties of MHD modes localized to edge
- Including: stability, initiation, nonlinear evolution, transport

Configuration:

- Any device that operates routinely with edge localized MHD instabilities
- For small devices, low aspect ratio advantageous → gives large edge current

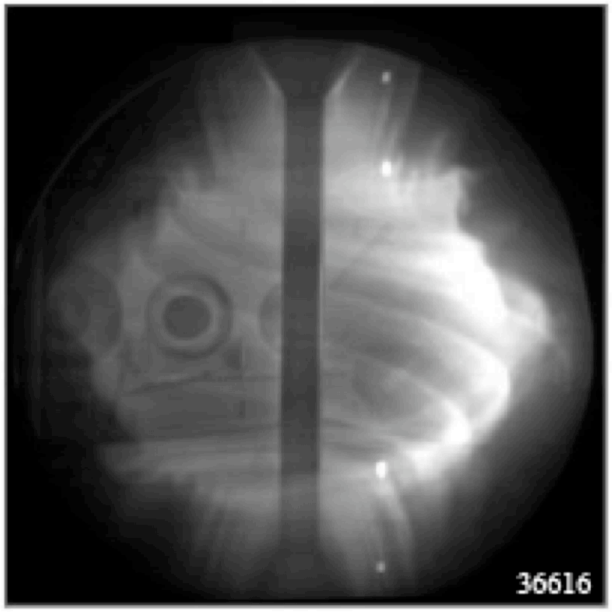
Limitations:

- Small devices: Large ρ_*, may have limiter instead of divertor

To mitigate limitations:

- Lower ρ_* at expense of increased collisionality

Case Study 3. Validation of models for linear and nonlinear dynamics of edge-localized MHD modes



Measurements:

- MHD equilibrium quantities,
- esp. edge localized current profile
- Small size allows probes
- Fluctuation diagnostics to track nl evolution

Modeling:

- ELITE – linear onset
- M3D, NIMROD for nonlinear evolution
- Sensitivity to profiles is key issue

Connection to other devices:

- ELMS are common to many devices
- Edge MHD activity in small devices is of peeling variety

Case Study 4. Validation of edge turbulence models via studies of turbulence dynamics in laboratory experiments with open field lines

Physics:

- Complexity of edge region
- Disparate fluctuations characteristics with different edge conditions
- Flow/turbulence interaction

Configuration:

- Open field line devices, e.g.: TORPEX, Helimak, CLM, HelCat, CSDX, LAPD
- Device diversity: vary sources, magnetic topology, species mix, ionization

Limitations:

- Large parallel losses, low T_i, large ρ_*, importance of neutrals

To mitigate limitations:

- Treat parallel losses in modeling, heat ions (e.g., RF), vary ρ_* with device, control neutral physics by changing ionization fraction

Case Study 4. Validation of edge turbulence models via studies of turbulence dynamics in laboratory experiments with open field lines

Measurements:

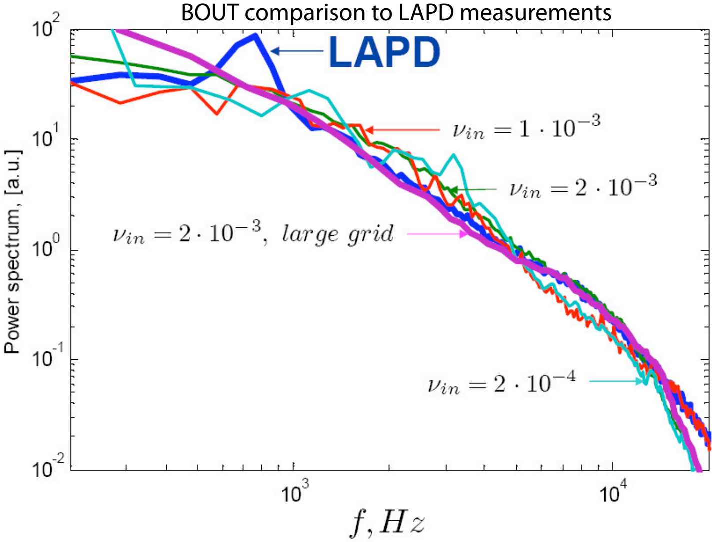
- Profiles of density, temperature, flow, potential
- Fluctuation characteristics, fluxes of heat, particles, momentum
- Configuration permits probes, imaging, microwave diagnostics, spectroscopy
- Neutral profile diagnostics

Modeling:

- Existing codes (BOUT) should include collisional and neutral effects, atomic physics
- Open field line configuration requires significant code modification

Connection to other devices:

- Edge processes present in all machines
- Wide variation as test bed for edge physics modeling



Case Study 5. Validation of RF sheath models

Physics:

- Amplification of sheath potentials by hybrid effect
- Nonlinear RF wave coupling between antenna and plasma facing components
- Causes damage to plasma facing components, impurity generation

Configuration:

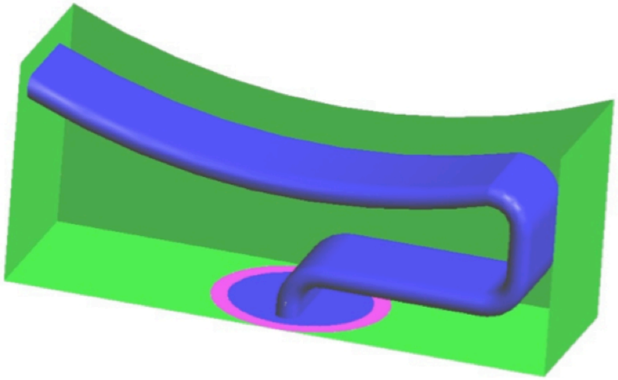
- Simple laboratory experiment supporting propagation of fast, slow magnetosonic waves; example: LAPD
- Access for measurement of wave fields and sheath potentials

Limitations:

- Antenna power may too low to replicate tokamak experiments
- Lower magnetic field strength

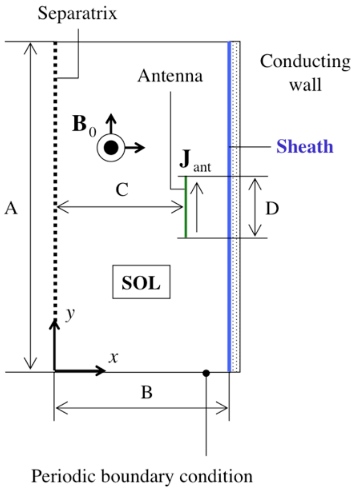
To mitigate limitations:

- Large power source
- Test RF-sheath theory over large range



Proposed antenna

Case Study 5. Validation of RF sheath models



Measurements:

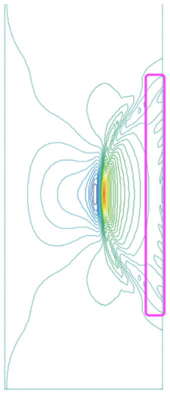
- Electric potential at strike plate
- Potential at antenna
- RF fields in plasma

Modeling:

- Existing 2D finite element wave code extended to cylindrical geometry
- Extension to 3D using poloidal mode decomposition desirable

Connection to other devices:

- Cylindrical geometry has similarities to tokamak edge
- Quantitative validation in simpler geometry will bolster confidence in extension to tokamak situation



Re(E_x)

Case Study 6. Validating fundamental mechanisms of turbulent transport in multiple channels

Physics: Feasibility –validation work if instability could be controlled

- Interrelationship of transport channels in ITG
- Characteristics of transport (e.g., diffusive or non diffusive?)
- Proximity to marginality
- Transport in multiple channels when modes combine (e.g., ITG and ETG)

Configuration:

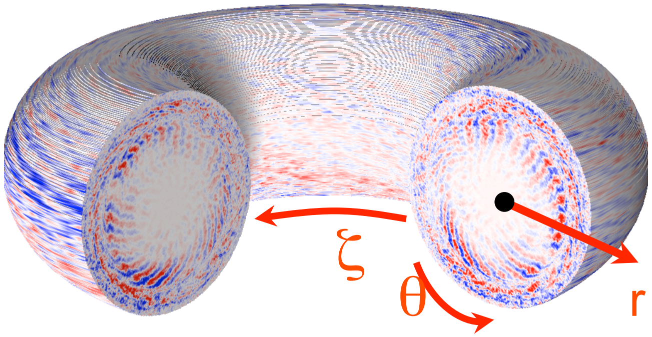
- Linear or toroidal – key is profile control, if only perturbatively, to control instability
- Low temperature for probe access

Limitations:

- Parallel losses, will plasma have a core?

To mitigate limitations:

- Treat parallel losses in modeling



Case Study 6. Validating fundamental mechanisms of turbulent transport in multiple channels

Measurements:

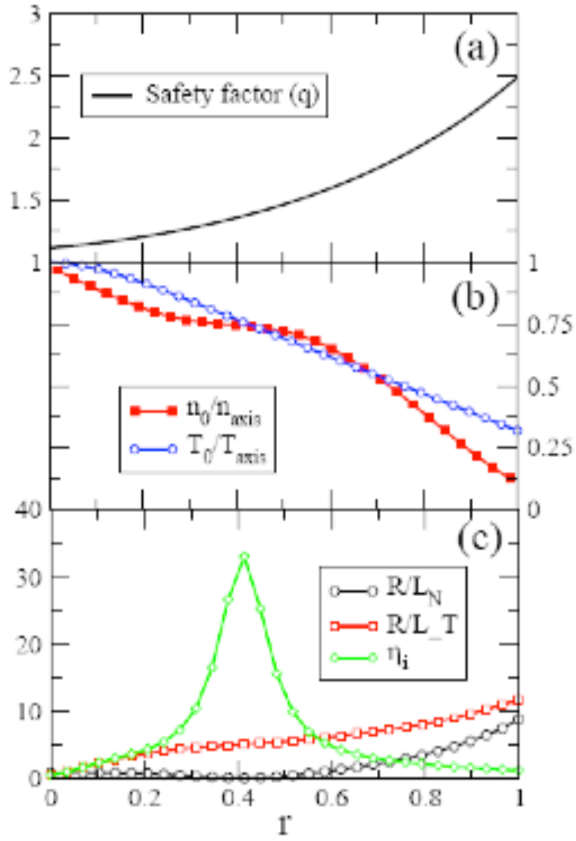
- Transport fluxes in each channel
- Profiles
- Emphasis on multiple channels: primacy hierarchy from fluctuations to fluxes

Modeling:

- For linear geometry, codes with parallel loss physics
- Test range of models from reduced to gyrokinetics, using information from multiple channels to understand effect of reductions

Connection to other devices:

- Relevant to high performance devices



Summary

Predictive capability requires validation at new level of rigor

For assurance that inner workings of models are correct:

- We have proposed creating hierarchy of validation experiments that peels back complexity in physics, geometry, interactions, and/or enhances diagnostic access

Case studies given as illustrations