MFE related abstracts for 2018 BOUT++ Workshop

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ELM crash with nonlinear toroidally axisymmetric flow and field

Haruki SETO[1], Xueqiao XU[2], Benjamin D. DUDSON[3], Masatoshi YAGI[1]

[1] National Institutes for Quantum and Radiological Science and Technology,
[2] Lawrence Livermore National Laboratory, [3] University of York
e-mail: seto.haruki@qst.go.jp

ELMs with toroidal axisymmetric (n=0) flow and fields driven by short wave-length instabilities are simulated at the first time by plasma fluid simulation code BOUT++ [1] with an improved Poisson solver and Poisson bracket [2]. In the original BOUT++ code, the n=0 net flow was set to be zero assuming the $E\times B$ flow balanced the ion diamagnetic flow without solving n=0 vorticity equation. Therefore, the zonal flows (the n=0 $E\times B$ flows) driven via the Reynolds stress are not considered which plays a role in some cases [3]. In addition, the n=0 magnetic field is also assumed to be negligibly small compared to the equilibrium magnetic field. These limitations are removed here and the impact of these effects is discussed.

The left figure summarizes the time evolution of toroidal power spectrum of internal energy and the time evolution of plasma energy loss released from the plasma edge during ELM crash described by a four-field peeling-ballooning model in a shifted circular equilibrium. In this simulation, the ion gyro-viscous force cancels with the Lagrangian derivative of the ion diamagnetic flow [4] so that the vorticity is described with the electrostatic potential. The inversed energy cascade from n=20~50 to the n=0 mode is observed during the ELM crash phase t=140t_A~240t_A and the energy loss level saturates after the nonlinear relaxation due to the generation of the radial electric field shear (E_r shear) as is shown in the right figures. The Reynolds stress generates the n=0 E_r shear and the pressure filaments are broken up by it, which results in the suppression of radial propagation of the pressure filaments. The n=0 parallel current is also generated by the n=0 E_r and filament structures of current are also observed.

In the presentation, we will report the numerical improvements introduced into the QST version of BOUT++ code. In addition to ELM crashes with and without n=0 flow and field by the present four-field model, ELM crashes with and without n=0 flow and field described by another four-field model with the ion gyro-viscos model in which the ion gyro-viscous force cancels with the convective derivative of the ion diamagnetic flow [5] will be also reported. In this model, the vorticity is described with the generalized flow potential including ion diamagnetic flow like the original BOUT++ code. These simulations will clarify the difference between the present work and the original BOUT++ code.

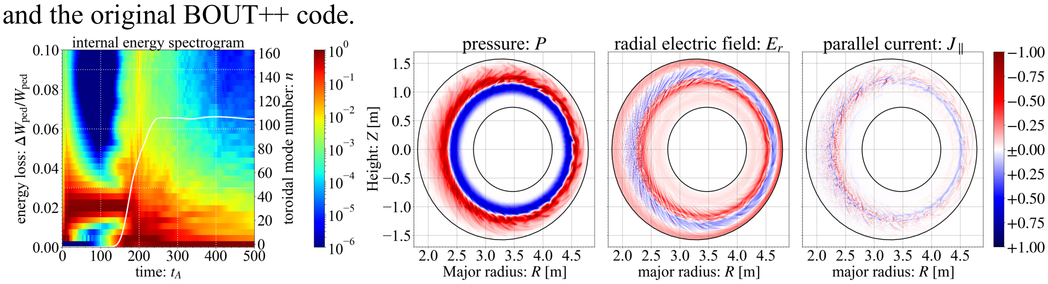

Figure: Time evolution of plasma energy loss (left y-axis) and that of toroidal power spectrum of internal energy during ELM crash (right y-axis) (left) and poloidal slices of pressure (left), radial electric field (center) and parallel current (right) after the nonlinear relaxation (t=500t_A) (right).

[1] B.D. Dudson *et al.*, Comput. Phys. Commun. **180** (2009) 1467-1480, [2] H. Seto *et al.*, submitted to Comput. Phys. Commun., [3] S. Pamela *et al.*, Plasma Phys. Control. Fusion **52** (2010) 075006, [4] R.D. Hazeltine *et al.*, Phys. Fluids **28** (1998) 2466, [5] Z. Chang and J.D. Callen, Phys Fluid B **4** 1766 (1992).

Edge Pedestal Collapse Simulations with Resonant Magnetic Perturbations

Juhyung Kim, S. S. Kim, Hogun Jhang
Advance Technology Research Center, National Fusion Research Institute, Daejeon

We present the edge pedestal collapse simulations with resonant magnetic perturbations in BOUT++ . It has been previously suggested that in the pedestal collapse driven by ideal ballooning instability, the ballooning-parity fluctuations can nonlinearly produce tearing-parity fluctuations, rendering magnetic field-line stochastic. It is found that the nonlinearly driven tearing fluctuations of high and low toroidal numbers can be modified in the presence of RMPs. The effect is significant with larger pressure and RMP strength. This finding implies the nonlinear dynamics of edge collapse. We report ongoing progress in nonlinear collapse simulations with RMPs.

In addition, we will discuss some numerical issues that hinder the progress in the simulations.

Flux driven GDB model for tokamak edge turbulence study

B. Zhu[1*], M. Francisquez[2], B. Rogers[2]

[1]Lawrence Livermore National Laboratory, Livermore, CA 94550
[2]Dartmouth College, NH 03755
*zhu12@llnl.gov

The flux driven global drift-ballooning (GDB) code is developed to study tokamak edge low frequency turbulence and transport, and their relationship to global profile evolution. The code employs a 3D electromagnetic fluid model that does not discriminate between equilibrium and perturbative contributions, capturing arbitrary amplitude fluctuations. Primitive plasma variables, including the E×B flow profiles, are evolved self-consistently in both closed-flux surfaces and the scrape-off-layer (SOL). A suite of numerical techniques, for example, boundary penalization method, field-line independent coordinate, multigrid solver and subcycling, are implemented to handle the linear and non-linear components of the model efficiently so as to support realistic discharge parameters (such as realistic deuterium mass ratio mi/me≈60) and yield good scaling on high performance computing (HPC) systems. GDB resolves turbulence slower than the ion gyrofrequency in simulations that capture the milisecond-scale evolution of global plasma profiles. With the explicit particle source (fed by KN1D model), we find that the global plasma and the spontaneous generated E×B flow profiles obtained from GDB IWL Alcator C-Mod L-mode simulations agree well with the MLP data.

Recent progress on pedestal and divertor physics towards long-pulse H-mode operation in EAST

Baonian Wan* for the EAST Team and Collaborators**
Institute of Plasma Physics, Chinese Academy of Sciences, Hefei 230031, China
*E-mail: bnwan@ipp.ac.cn

Recently, fully non-inductive steady-state H-mode plasma has been successfully sustained over 100 s on EAST for the first time, with an optimized pedestal/divertor plasma operation. Several important progress on pedestal and divertor experiments on EAST for future advanced steady-state operation far beyond 100s with ITER-like W divertor have been achieved, including: (i) Development of small/no ELM regime, (ii) understanding of pedestal instabilities and giant ELM control, (iii) active handling of the particle and heat flux deposited on divertor. To meet with more critical particle and power exhaust challenges, the lower divetor of EAST will be upgraded from current carbon to actively water-cooling W structure with a 'Neutral Trap Corne' design. Based on these new physics progresses and enhanced capability, the compatibility between pedestal and divertor can be further improved, to facilitate long-pulse H-mode operation over 400s, 10 MW power injection over 100s in the near future. These program is oriented to support ITER and CFETR long pulse operation, which some of critical issues will also be addressed.

** See appendix of B. N. Wan et al., Nucl. Fusion 57, 102019 (2017)

Introduction to Kinetic Physics in Tokamak Boundary Plasma

C-S Chang
Princeton Plasma Physics Laboratory
Princeton University

Unlike the core plasma, tokamak boundary plasma is in a non-equilibrium or a far-from-equilibrium thermodynamic state. Individual particle orbits can significantly deviate from the usual equilibrium statistical behaviors, transport may not obey Fick's law, the transport time-scale may not be diffusive time-scale, plasma can easily become non-Maxwellian, the conventional fluid closures based on the near-equilibrium thermodynamics –including the well-utilized CGL closure and Braginskii viscosity – may not be valid, and plasma turbulence may be of different type from that of core plasma. A kinetic simulation may be needed for higher fidelity understanding of the boundary physics and for improvement of fluid closures. This talk will introduce the kinetic aspect of the boundary plasma that may not be easily captured by fluid moments equations and that may help improve fluid simulations through collaborative effort. The spatial region of discussion will include the H-mode pedestal, the magnetic separatrix and the X-point, and the scrape-off region that is in contact with the material wall. Neutral particle kinetics will also be discussed.

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Simulation of the Lithium pellet injection in a divertor geometry using the BOUT++ transport code

Y. M. Wang[1], X. Q. Xu[2], Z. Wang[3], N. M. Li[4], Z. Sun[1], T. Y. Xia[1], J. S. Hu[1] and X. Gao[1]

[1]Institute of Plasmas Physics, Chinese Academy of Sciences, Hefei 230031, China
[2]Lawrence Livermore National Laboratory, Livermore, CA 94550, USA
[3]Los Alamos National Laboratory, Los Alamos, NM 87545, USA
[4]School of Physics, Dalian University of Technology, Dalian 116024, China

A novel model predicting the Lithium pellet injected into the plasmas has been developed to simulate the effect of the background plasma, as well as the Lithium impurity density and temperature. The pellet will ablate due to the heat from the background plasma, and the neutral gas shielding (NGS) model is used to describe this physics process. After the ablation, the neutral gas will expand, and form an elongated plasmoid along the magnetic line. The neutral gas plasmoid shielding (NGPS) model has been used to calculate the initial neutral gas density inside the plasmoid.

In the new BOUT++ transport code, the ionization, charge exchange and recombination of the impurities use the data from the ADAS database. A grid generated from the C-mod lower single null equilibrium has been used to generate the grid for BOUT++ simulation. The scan of the pellet parameters such as the pellet size, injection velocity has been conducted. The comparison of the simulation results with the experiments results will be conducted in the future.

Numerical simulation of lithium granule injection on tokamak edge plasma

Fang Gao, Lijun Liu, Jinyuan Liu, Jizhong Sun

Key Laboratory of Materials Modification by Laser, Ion, and Electron Beams (Dalian University of Technology), Ministry of Education, Dalian University of Technology, Dalian 116024, China

Abstract:

To understand how a Li pellet affects the background plasma, the edge plasma code SOLPS combined with a neutral-gas-shield ablation model has been employed to simulate the transport of Li species in the edge plasma during one and a series of Li pellet injections in a typical EAST H-mode plasma. The simulation results show that a Li pellet with size of 1.0 mm or over in radius can penetrate the separatrix at velocity of ~100 m/s， and that the electron temperature drops quickly where the pellet passes by while the electron density experiences a longer time to respond. The plasma pressure at the pedestal region grows rapidly with the pellet size; the pressure gradient changes even more drastically. This work indicates that without accumulative contributions, only a pellet with a size of 1.5 mm or above in radius at an injection velocity of 100 m/s is likely to provide a pressure perturbation to trigger an ELM under the plasma parameters used here.

Key words： Lithium granule; injection; scrape-off layer; SOLPS code.

Divertor particle and heat fluxes simulation during ELM in H-mode discharge on HL-2A tokamak

Xiaoxue He[1,2], Zhanhui Wang[2] and Yue Liu[1,*]
[1]Key Laboratory of Materials Modification by Laser, Ion and Electron Beams (Ministry of Education), School of Physics, Dalian University of Technology, 116024, China
[2]Southwestern Institute of Physics, Chengdu 610041, China
*liuyue@dlut.edu.cn

Abstract

In fusion experiments on tokamak devices, edge localized mode (ELM) is a serious threat for plasma facing materials of divertor plates and wall due to exhausting the particle and heat. Many research works focus on the particle and heat transports in the edge, SOL and divertor regions during ELM in H-mode discharge to understand their physics. In this work, the distribution and evolution of the transient particle and heat fluxes during ELM bursts are simulated numerically by using a BOUT++ code with six-field two-fluid module in HL-2A divertor geometry. Experiment plasma profiles of shot #24953 in an H-mode discharge on HL-2A tokamak are adopted as the initial conditions in the simulation. The results of the linear simulation show the resistive ballooning mode is unstable. The nonlinear simulation results of particle and heat fluxes during ELM bursts are compared with the experimental results measured by divertor plate probes or Bolo meter. The underlying physics of the particle and heat transport in the edge, SOL and divertor region are also studied.

The RF sheath boundary condition in BOUT++ simulation

B. Gui, T. Y. Xia, X. Q. Xu, J.R. Myra and X. T. Xiao
Institute of Plasma Physics, Chinese Academy of Sciences

The equilibrium electric field that results from an imposed DC bias potential, such as that driven by a radio frequency (RF) sheath, is calculated using a new minimal two-field model in the BOUT++ framework. Biasing, using an RF-modified sheath boundary condition, is applied to an axisymmetric limiter, and a thermal sheath boundary is applied to the divertor plates. The penetration of the bias potential into the plasma is studied with a minimal self-consistent model that includes the physics of vorticity (charge balance), ion polarization currents, force balance with $E \times B$, ion diamagnetic flow (ion pressure gradient) and parallel electron charge loss to the thermal and biased sheaths. It is found that a positive radial electric field forms in the scrape-off layer and it smoothly connects across the separatrix to the force balanced radial electric field in the closed flux surface region. The results are in qualitative agreement with the experiments. Plasma convection related to the $E \times B$ net flow in front of the limiter is also obtained from the calculation.

Dynamics fuel recycling in Tokamak: effects of material surface processes on dynamics wall outgassing

J. Guterl[a,b], P. Snyder[b]

[a] *Oak Ridge Associated Universities, USA*
[b] *General Atomics, San Diego, CA USA*

Dynamics response of wall recycling to variations of plasma particle and heat load on wall material may perturb SOL plasma, and generate wall outgassing driven instability [1]. Wall recycling is nevertheless usually modeled assuming constant recycling coefficients. Macroscopic models describing the dynamics of wall retention and recycling, such as FACE [2], must be developed. Hydrogen wall recycling is mainly driven by the implantation and desorption of hydrogen in the implantation layer beneath the material surface. We present here some preliminary investigations on surface and sub-surface processes governing hydrogen desorption from divertor material (here W) using molecular dynamics simulations. Thermal desorption of hydrogen from W surface is simulated at various temperature and coverage. The activation energy of molecular desorption of hydrogen is about 1.6-1.9eV, in agreement with experimental estimations.

H desorption induced by incoming H ions may also be comparable to thermal desorption. Ion-induced desorption of H is characterized by simulating H particles impinging onto a fully covered W surface. At low incident energy <1eV, impinging hydrogen particles either deposit onto W surface, or induce molecular desorption. In contrast, impinging hydrogen particles at higher incident energy ~10eV induce atomic desorption of one or two separate H atoms. Effects of ion-induced desorption on wall outgassing are discussed.

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[2] Smirnov, R. D., J. Guterl, and S. I. Krasheninnikov. *Fusion Science and Technology* 71.1 (2017)

Quasi-coherent mode simulation during inter-ELM period in HL-2A

T. F. Tang[1], H. Shi[1], Z. H. Wang[2], W. L. Zhong[2], T. Y. Xia[3], X. Q. Xu[4],

D. Z. Wang[1, *]

School of Physics, Dalian University of Technology, 116024, China

Southwestern Institute of Physics, Chengdu 610041, China

Chinese Academy of Sciences, Institute of Plasma Physics, Hefei 230031, P. R. China

Lawrence Livermore National Laboratory, Livermore, CA 94550, USA

**Corresponding author: D. Z. Wang, wangdez@dlut.edu.cn.*

We have performed linear and nonlinear simulations to study the driven mechanism of quasi-coherent modes (QCM) during inter-ELM period in HL-2A, using a six-field two-fluid module in BOUT++ framework. Linear simulations show the Resistive-Ballooning mode (RBM) is unstable. And the QCM inside the separatrix at mid-plane has been reproduced in the nonlinear simulation. Poloidal wave number and frequency spectra from fluctuations analysis are comparable to the experimental results, the corresponding m and n matches. Phase shift between the electrical potential and the density fluctuation also matches. Theoretical predictions of the poloidal wave number and the frequency are in good agreements with the experimental and the simulation results. Based on linear RBM scans of temperature and density, we successfully explain other experimental observations of the QCM. Within the QCM (RBM) during the pedestal recovery phase, two feedback mechanism have been found, which provide a constrain of the pedestal structure.

A Landau Fluid closure for Arbitrary Frequency and its implementation in numerical code

L. B. Wang[1] and X. Q. Xu[2]

[1] *Peking Univ.*

[2] *LLNL*

The perturbed heat flux and temperature for Landau damping case are calculated directly. The relationship between these two physical quantities is the same as Hammett-Perkins' closure in low frequency limit. To bridge the low and high frequency limit, the harmonic average form of kinetic LF closure is developed which shows that the transport is non-local both on space and time. The harmonic average closure depends on wave frequency and yields a better agreement with kinetic response function than that of Hammett-Perkins' closure. The implementation in numerical code is also presented, based on an approximation by a sum of diffusion-convection solves (SDCS). The three moment Landau-fluid model has been implemented in the BOUT++ code using the SDCS method for the harmonic average form of LF closure. Good agreement has been obtained for the response function between driven initial-value calculations using this implementation and matrix eigenvalue calculations using SDCS implementation of the LF closure.

Exploring ELM-free and ELM suppressed operation for CFETR

Yiren Zhu[1], V.S.Chan[2,3], Zeyu Li[4], Xiang Jian[1]

1. Laboratory of Advanced Electromagnetic Engineering and Technology,Huazhong University of Science and Technology,Wuhan 430074,China;
2. School of Nuclear Science and Technology,University of Science and Technology of China,Hefei 230026,China;
3. General Atomics,San Diego,CA92186,USA;
4. State Key Laboratory of Nuclear Physics and Technology, School of Physics, and Fusion Simulation Center, Peking University, Beijing 100871, China

With the proposed China Fusion Engineering Test Reactor (CFETR) as a next step in China fusion development, identifying stable operation regimes with good performance and acceptable heat and particle control is a key goal of CFETR engineering design. To achieve this goal Type I ELMs with large amplitudes have to be avoided in order to prevent excessive erosion of the divertor target material.

This study investigates various methods to achieve robust grassy_ELM or ELM-free operations in CFETR. Using a combination of EPED and ELITE, we map out the operating space of the CFETR pedestal,and explore the changes in ELM characteristics along the marginal stability boundary. The pedestal current and density for optimized performance is identified. The ELM behavior is classified using BOUT++ simulation. Ways to suppress or avoid ELMs will be discussed.

Hands-on exercises: Hermes and SD1D

Ben Dudson
University of York

Hermes is a 2D or 3D BOUT++ model which has been developed for flux-driven plasma transport and turbulence simulations, including self-consistent neutral gas interactions. Particular attention has been paid to conservation properties in constructing the model and numerical schemes, important for high recycling regimes with strong plasma-neutral interactions. The Hermes model has been applied to simulations of linear devices, DIII-D and MAST-Upgrade tokamak geometries.

SD1D is a simplified 1D version of Hermes which includes the plasma dynamics parallel to the magnetic field, fluid neutrals, and a fixed fraction impurity radiation model using ADAS data. This time dependent model can be used to study plasma detachment dynamics, the impact of magnetic geometry and neutral gas confinement and other divertor studies.

This hands-on session will begin with setting up, running and analysing an SD1D simulation. The Hermes code will then be introduced and we will cover setting up and running 2D transport simulations.

The SD1D code is available from https://github.com/boutproject/SD1D
The Hermes code is available from https://github.com/boutproject/hermes

Overview of the BOUT++ Code Structure

Ben Dudson
University of York

This talk will give an introduction to the numerical methods and internal structure of BOUT++. BOUT++ has been applied to many different problems, solving equations using methods and geometries which were not originally intended. As a result the code has been rewritten or significantly restructured at least three times, each time becoming more flexible and (usually) faster.

The aim of this talk is to show the capabilities of BOUT++ for doing interesting science, and to show the advantages and limitations of the way BOUT++ is currently structured. This should be useful for users, to better understand the code and what happens when it goes wrong, and for anyone interested in extending BOUT++ in another new direction.

Starting with the method of lines which separates the code into time integration and spatial operators, we will then go into the variety of schemes available. A mostly object-oriented approach is used to separate implementations from interfaces, so that the method used can often be changed with an input option. As a result the same patterns of code organisation are repeated. By the end of this talk this structure will hopefully be clearer, enabling you to find relevant parts of the code more quickly.

The end of the talk will discuss current and recent work, including changes to enable vectorisation and OpenMP parallelisation, and experimental approaches to improving efficiency and scaling.

BOUT++ Performance and Scaling

Ben Dudson
University of York

This talk will present and discuss the factors which limit the performance of BOUT++ and its ability to scale beyond a few thousand cores. This will start with a presentation of the reduced plasma fluid and gyrofluid models typically solved with BOUT++, their dispersion relations and fast timescales.

Preconditioning of the fully implicit time stepper usually used (SUNDIALS' CVODE) gives significant improvements in some simplified cases, but the dispersive high frequency waves present in most models of interest make finding an efficient preconditioner difficult in general geometries with complex boundary conditions like plasma sheaths. Previous and current attempts to use "physics based" preconditioning, Implicit-Explicit, Jacobian coloring and AMG methods will be described, along with benchmarking and some analysis of bottlenecks.

Removal of the magnetosonic fast wave in reduced plasma models introduces a coupling to a stream function in a similar way to incompressible fluid dynamics. This stream function is the solution to an elliptic equation, which must be calculated at each timestep. Solving this elliptic equation is often a bottleneck to scaling. Complex geometries involving various topologies (x-points) further complicate the problem: PETSc with Hypre preconditioning has been found to be effective in these cases, but typically consumes a large fraction of the overall runtime. Opportunities for improvements will be discussed.

Hands-on exercises: GLF module
Gyro-Landau-Fluid module in BOUT++

Ben Zhu
LLNL

To better describe the hot, weakly collisional plasma at the top of pedestal region, a sophisticated Gyro-Landau-Fluid (GLF) module has been developed in the BOUT++ framework. [Ma and Xu, Nuclear Fusion, 57, 016002 (2017)] This newly added GLF module captures several important kinetic effects which have been neglected in the previous three-field or six-field model, including collisional and collisonless (Landau) damping, toroidal resonance, temperature anisotropy and so on.

This hands-on session covers: (1) the basics of GLF, including various closures used in this particular module; (2) numerical implementation of GLF equations; (3) code setup and run a few examples, e.g., 1D Landau damping, linear growth rate of kinetic Alfven wave in slab geometry and/or kinetic ballooning modes in toroidal geometry.

Prediction of Divertor Heat Flux width on ITER and CFETR Using BOUT++

Ze-Yu Li[1,2], Xue-Qiao Xu[2,1], Na-Mi Li[3,2], V S Chan[4,5]

[1]*State Key Laboratory of Nuclear Physics and Technology, School of Physics, and Fusion Simulation Center, Peking University, Beijing 100871, China*

[2]*Lawrence Livermore National Laboratory, Livermore, CA 94550, USA*

[3]*School of Physics, Dalian University of Technology, Dalian 116024, China*

[4]*School of Nuclear Science and Technology, University of Science and Technology of China, Hefei 230026, China*

[5]*General Atomics, San Diego, CA 92186, USA*

Investigation on the turbulent transport dynamics in Scrape-off-layer (SOL) and divertor heat flux width prediction are performed for ITER and China Fusion Engineering Test Reactor (CFETR). Both BOUT++ transport and BOUT++ turbulence codes are applied to capture the physics on different spatial-temporal scale. Simulations start with ITER 15MA baseline scenario (2015, S.H. Kim) and CFETR R7.2 Hybrid scenario (R=7.2m, B_T =6.5T) respectively. In BOUT++ transport code, the plasma profiles (n_i, T_i, T_e) and radial electric profile(E_r) are evolved to steady state. Transport coefficients are calculated from the plasma profiles inside separatrix, then extending to the SOL. The plasma profiles inside the separatrix are taken from those calculated using CORSICA and ONETWO codes for scenario studies. Parametric scan for anomalous thermal diffusivity (χ_i, χ_e) is also performed. Which shows that when diffusivity is smaller than a critical χ_{crit}, heat flux widths keep almost unchanged, which is consistent with Goldston's HD model. Otherwise it would increase following the $\lambda_q \propto \chi^{1/2}$ scaling. The perpendicular heat flux crossing the separatrix is drift-dominant when $\chi_{i,e} < \chi_{crit}$, while it would become turbulence dominant when $\chi_{i,e} > \chi_{crit}$, which would build a bridge from drift dominate regime to turbulence dominate regime for determining λ_q. BOUT++ 6-field turbulence code was also carried out to study pedestal and SOL turbulence dynamics and the following transport. In the turbulence simulation, the pedestal structure (0.90x, 0.95x, 1.00x) is found to be important in determine the effective thermal diffusivity and result in different divertor heat flux widths. Radial transport carried out by electro-magnetic effect is found to be the main contributor of the transport across separatrix in the turbulence simulation.

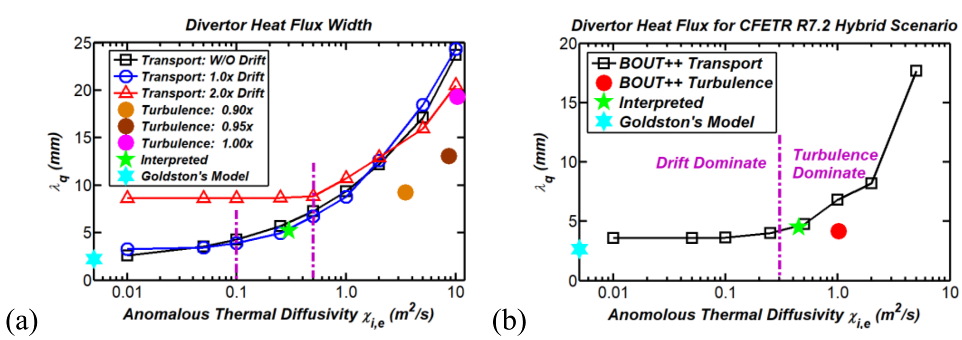

Figure 1. Divertor heat flux width vs. anomalous thermal diffusivity. (a) ITER; (b) CFETR

Impurity migration pattern simulated by test particle module under BOUT++ framework

Xiaotao Xiao, Xueqiao Xu, and Bin Gui
Institute of Plasma Physics, Chinese Academy of Sciences

A test particle module is developed under BOUT++ framework. The guiding center orbits in real divertor geometry can be calculated. The turbulence transport is implemented by random walk model. Impurity migration patterns under different turbulence transport levels are simulated by this module. As transport increase, migration pattern is modified significantly. More particles are lost and the lost at low field side boundary increase significantly.

Possible Inversion of the Sheath Potential Under Strong Thermionic Emission from Tungsten Divertor Plates

M. D. Campanell, M. V. Umansky

Lawrence Livermore National Laboratory, Livermore, California 94551, United States of America

campanell1@llnl.gov

Electron-emitting sheaths are important to the plasma-surface interactions in many systems including tokamaks. Past theories dating back to Hobbs and Wesson assumed that the floating sheath potential must be negative [1]. Under strong emission, a small potential well (virtual cathode) was predicted to form to suppress some emitted electrons. This "space-charge limited" (SCL) sheath concept was used for sheath transmission factors in scrape-off-layer fluid models (see Stangeby's book). Recent analyses predict that the heating of tungsten divertor plates can lead to sufficient thermionic emission for a SCL sheath [2].

Our study shows that strongly emitting sheaths in experiments should not be SCL. Theoretical models [1] and simulation demonstrations [2] of SCL sheaths have always omitted collisions. We demonstrate [3] that when charge-exchange collisions are present, ions inevitably get trapped in the virtual cathode and their accumulation forces a transition to the inverse regime with a positive (ion-repelling) sheath potential. In the inverse regime, the force balance of electrons and ions throughout the plasma, and their fluxes to the surface, differ from the conventional regime. An inverse regime may offer benefits to divertors. The lack of ion acceleration reduces sputtering. Also in the inverse regime, a high density of cold thermionic electrons (T_{emit} < 1eV) dominates the quasineutral plasma near the target. Under certain conduction-limited conditions this will significantly cool the target plasma and facilitate detachment, reducing the need to inject impurities. Ongoing investigations will determine whether intentional inducement of the inverse regime would be feasible and beneficial.

Inverse sheaths will change the interpretation of emissive probe potential measurements in divertor plasmas and other devices. The measured probe floating potential was long assumed be about 1Te below the plasma potential according to SCL sheath theory. Our inverse sheath model [3] suggests that a strongly emitting probe should float slightly above plasma potential, which is actually observed in some experimental studies of probes [4,5]. We also demonstrate that SCL sheaths break down and transition to an inverse mode even when the surface is a current-carrying cathode with a large negative bias [6]. This will alter the operation of plasma applications that rely on hot cathodes such as thermionic discharges, thermionic converters, and thermionic spacecraft tethers.

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Implementation in BOUT++ and Testing of a 3D Extension of the SOLT Model for Coupled Simulations of Scrapeoff-Layer Turbulence and RF Effects*

A. M. Dimits or M. V. Umansky

with I. Joseph, T. Rognlien, LLNL, J. Myra, D. A. Russell, Lodestar Research, S. Shiraiwa, MIT, C. Lau, E. Martin, ORNL, T. Jenkins, D. Smithe, Tech-X, R. W. Harvey, Y. Petrov, CompX

Progress is reported on development of a 3D extension of the SOLT tokamak edge/scrapeoff-layer (SOL) turbulence model [1] in the BOUT++ framework [2]. Like the original SOLT, the 3D version models the outer midplane region of a tokamak around the last closed flux surface, and the divertor target plates are represented by sheath boundary conditions. The extended 3D version includes parallel variations of plasma fields and electron dynamics along the magnetic field line. Testing of the model includes verification of linear instabilities supported by the model, drift-resistive-ballooning and conducting-wall modes, and nonlinear solutions for isolated plasma filament propagation in the SOL.

Progress is also reported on using this model as the turbulence and transport component in coupled simulations of turbulence and ICRF (Ion Cyclotron Range of Frequencies) codes and models. The effects of boundary conditions representing RF launching structures on transport equilibria and turbulence are studied. The simplest such boundary conditions involve regions on the outer flux surface biased at an effective RF-sheath potential relative to the parts of the surface not in these regions. We compare solutions between the BOUT++ models and the UEDGE code for cases where these regions are axisymmetric. Simulations in which biased structures impinge into an outer volume of the BOUT++ model are also studied and compared with those obtained with biased regions (only) on the outer surface. Work is also reported on the transfer of data from BOUT++ simulations to the edge-relevant ICRF codes, e.g. for simulations of RF scattering and propagation, including development of a generally useful data format and API.

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Study of high β_N plasmas on EAST tokamak

Xiang Gao[1,2], Long Zeng[1], Yaowei Yu[1], Haiqing Liu[1], Guoqiang Li[1], Gongshun Li[2], Huishan Cai[3], Xuemei Wu[4], Kazuaki Hanada[5], Yu Gao[6], Tingfeng Ming[1], Tao Zhang[1], Yao Yang[1], Zixi Liu[3], Feifei Long[1], Yukai Liu[1], Muquan Wu[2], Haoming Xiang[1], Kai Li[1], Xiang Zhu[2], Fubin Zhong[1], Bo Lyu[1], Yinxian Jie[1,2], Qing Zang[1,2], Hang Li[2], Yunfeng Liang[6], Xianzu Gong[1], Jiangang Li[1,2], and the EAST team[1]

[1]Institute of Plasma Physics, Chinese Academy of Sciences, P.O. Box 1126, Hefei, Anhui 230031, People's Republic of China

[2]Advanced Energy Research Center, Shenzhen University, Shenzhen 518060, People's Republic of China

[3]Department of Modern Physics, University of Science and Technology of China, Hefei, Anhui 230026, People's Republic of China

[4]College of Physics, Soochow University, Suzhou 215006, People's Republic of China

[5]Research Institute for Applied Mechanics, Kyushu University, 816-8580, Fukuoka, Japan

[6]Forschungszentrum Juelich GmbH, IEK-4, 52425 Juelich, Germany

E-mail: xgao@ipp.ac.cn

Abstract. Sustained high normalized beta ($\beta_N \sim 1.9$) plasmas with an ITER-like tungsten divertor have been achieved on EAST tokamak recently. The high power NBI heating system of 4.8 MW and the 4.6 GHz lower hybrid wave of 1 MW were developed and applied to produce edge and internal transport barriers in high β_N discharges. The central flat q profile with $q(\rho) \sim 1$ at $\rho < 0.3$ region and edge safety factor $q_{95} = 4.7$ is identified by the multi-channel far-infrared laser polarimeter and the EFIT code. The fraction of non-inductive current is about 40%. The relation between fishbone activity and ITB formation is observed and discussed.

Keywords: normalized beta, fishbone, tungsten divertor

Coupling a transport solver to global turbulence simulations

Parker, Jeff
Lawrence Livermore National Laboratory

Predictive modeling with transport solvers has tended to use surrogate models, such as quasilinear transport models, to represent turbulent fluxes. One route to improved predictive modeling is instead to couple with direct numerical simulations (DNS) of turbulence. We have coupled the transport code Tango to the gyrokinetic code GENE and show that this kind of coupling can be successful. For example, we have found steady-state solutions for the temperature profile in response to a specific heating source, where the turbulent transport is computed by GENE. One of the main challenges is the numerical algorithm for the coupling, which must overcome stiff nonlinearities. An additional complication of coupling a transport solver to turbulence simulations rather than a surrogate model is that the fluctuations hinder convergence, and we analyze this issue.

Collisional Landau Fluid Physics Models*

I. Joseph[1], A. M. Dimits[1] and Jeong-Young Ji[2]

[1]*Lawrence Livermore National Laboratory, Livermore, CA*
[2]*Utah State University, Logan, UT*

e-mail: joseph5@llnl.gov

This talk reviews the present status of collisional Landau fluid plasma models that accurately bridge the gap between collisionless kinetic and collisional fluid regimes. Accurate linear nonlocal closures have been developed for the Chapman-Enskog model [1] and for the 3+1 anisotropic pressure model ($n,u_{\|},p_{\|},p_{\perp}$) [2-3]. The extended models include the anisotropic thermal and electrical conductivities as well as the parallel thermal force and the heat flux generated by relative flows. The resulting plasma physics models are potentially quite useful for describing the edge of magnetized fusion devices.

*Work performed by LLNL under US DOE contract DE-AC52-07NA27344.

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Nonlinear ICRF interactions with the boundary plasma

J. R. Myra, Lodestar Research Corporation*

Plasma heating and current drive with ion cyclotron range of frequency (ICRF) waves has been quite successful in past tokamak experiments and is foreseen to play an important role in ITER. However, unwanted interactions with the scrape-off layer (SOL) plasma and material surfaces also occur in some regimes of operation. In this tutorial presentation, RF interactions that induce, modify or enhance sputtering, surface power dissipation, edge transport and plasma flows are discussed. Although RF waves and edge plasma turbulence exist on disparate time scales, they are coupled by nonlinear RF-driven sheaths on the boundaries, nonlinear ponderomotive forces, wave propagation and scattering, especially in the SOL near an antenna. The tutorial will focus on underlying physical mechanisms for these processes and their interactions.

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Hands-on exercises: Transport code

Nami Li

DLUT/LLNL

Transport module is developed with all drifts, including self-consistent calculation of radial electric field. The radial transport coefficients are calculated by using the interpretive approach, which can fix the profiles inside the separatrix to experimental profiles and calculate the profiles in the SOL by the given boundary conditions. This time dependent model can be used to study edge plasma transport, radial electric field and divertor heat flux studies. The transport model has been applied to simulations of DIII-D, C-Mod, EAST and ITER tokamak geometries. This hands-on session will begin with setting up, running and analyzing 2D transport simulation.

This code can be download from the nersc git repository.

Simulations of divertor heat flux widths using BOUT++ transport code with drifts

N.M. Li[1,2], X.Q. Xu[2], Dan Brunner[3], J.W. Hughes[3], B. LaBombard[3], J.L. Terry[3], J.Z. Sun[1], and D.Z. Wang[1]

linami@mail.dlut.edu.cn

[1]*School of Physics, Dalian University of Technology, Dalian 116024, China*

[2]*Lawrence Livermore National Laboratory, Livermore, CA 94550, USA*

[3]*MIT Plasma Science and Fusion Center, Cambridge MA, USA*

The BOUT++ fluid transport code has been developed with all drifts and the sheath potential in the SOL. Transport coefficients are calculated from the experimental profiles inside separatrix, then extending to the SOL. The calculated steady state radial electric field (E_r) has been validated with experimental measurements from a C-Mod discharge using charge exchange recombination spectroscopy. The magnitude of E_r is similar to the experimental data while the width is narrower. However, the simulated E_r profile is similar to the main ion diamagnetic term inferred from Thomson scattering profiles of electron temperature and density. Instrumental effects may in part explain this discrepancy. In order to understand the impacts of drifts vs. turbulent transport on the divertor heat flux width, a set of four C-Mod EDA H-mode discharges with lower single null divertor configuration are simulated. BOUT++ transport simulations with all drifts included yield similar divertor heat flux width λ_q to experimental measurements varying within a factor of 2 and show a similar trend to the Goldston's HD model. In simulations, the power across the separatrix increases with current, possibly due to increasing ohmic heating power. For C-Mod discharge, the drifts dominate the cross-field transport and the heat flux width is sensitive to the temperature neat the separatrix. Magnetic drift has a significant influence on the divertor heat-flux widths, while the ExB drift further decreases the heat flux width by 10%~25%, which improves Goldson's model.

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Progress in simulating scrape-off layer plasma dynamics with STORM

F. Riva,* F. Militello, S. Newton, T. Nicholas, J. T. Omotani, and N. R. Walkden
CCFE, Culham Science Centre, Abingdon, Oxon, OX14 3DB, UK

The STORM module of BOUT++ [1] has been developed in the last few years to investigate plasma turbulence and the dynamics of isolated filaments in tokamak scrape-off layer (SOL) conditions. It dynamically evolves a set of three-dimensional two-fluid drift-reduced Braginskii equations in the cold ion limit, retaining the parallel ion dynamics, as well as finite electron inertia and electron thermal effects. These equations are completed by the Bohm-Chodura boundary conditions, applied to describe the plasma properties at the magnetic pre-sheath entrance, where the validity of the drift approximation breaks down.

The STORM model was developed in successive stages by gradually including additional physical effects. Initially, assuming isothermal electrons, it was used to investigate the evolution of isolated filaments in slab geometries, with the effects of magnetic curvature and gradients artificially introduced in the model. To this end, steady state background equilibrium fields with variation only in the parallel direction were produced with ad hoc plasma sources, on top of which a density perturbation was seeded. The three-dimensional profiles were then evolved with STORM self-consistently, with no separation between equilibrium and perturbations. These isothermal simulations revealed how the filaments' amplitude, size, and perpendicular shape impact the filament motion [2, 3]. The isothermal model was also used to investigate the impact of enhanced parallel resistivity on filament dynamics, showing that an increase of the resistivity near the divertor plates leads to a suppression of parallel currents to the sheath. As a result, filaments with the smallest perpendicular length scales, which were inertially limited at low resistivity, were unaffected by the increase of the resistivity, while larger filaments displayed a faster radial velocity [4]. An evolution equation for the electron temperature was then included in STORM. This allowed the role of thermal effects on the dynamics of isolated filaments to be studied, revealing that, when the pressure perturbation within the filament is supported primarily through a temperature increase as opposed to density, filaments start spinning and their propagation in the radial direction is significantly reduced [5]. The STORM thermal model was also used to characterize how pairs of SOL filaments interact with each other, showing that their interaction is weak unless the filaments are in close proximity, i.e.

*Electronic address: fabio.riva@ukaea.uk

Linear Simulation of PBM in High-beta Plasmas

C. K. Sun[1], X. Q. Xu[2], B. Li[3], and P. F. Li[1]

[1] *Fusion Simulation Center, School of Physics, Peking University, Beijing 100871, China*

[2] *Lawrence Livermore National Laboratory, Livermore, California 94551, USA*

[3] *School of Physics and Nuclear Energy Engineering, Beihang University, Beijing 100191, China*

We present the 3D linear simulations of edge plasma instabilities based on the shifted circular geometry equilibrium using the 3-field peeling-ballooning model and gyro-Landau-fluid (GLF) model under the BOUT++ framework. A series of realistic equilibria are generated by a global equilibrium solver CORSICA, where the Shafranov shift, elongation effects and bootstrap current are included. It shows that when increasing the pressure gradient and the fraction of bootstrap current, the magnetic surfaces shift outwards. α and the safety factor q increases, but the magnetic shear s in the pedestal decreases, forming negative shear in the pedestal eventually. The linear growth rate spectrum of the peeling-ballooning modes (PBM) is shown in a wide range of pressure gradient and parallel current density in the pedestal region.

Simulations of ideal ballooning modes show that it reaches the second stability region locally, but not globally because of the distribution of α and s. With the diamagnetic effects and current drive included, the simulation results of peeling-ballooning modes (PBM) using the reduced fluid model show that the unstable region of PBM in high-beta cases decreases in both beta and toroidal mode number.

The bootstrap current destabilizes the PBM in low-beta cases, but stabilizes the high-n modes in the high-beta cases. The simulations with different fractions of bootstrap current indicate a trend for the existence of the high beta peeling-ballooning mode stability region. Taking the kinetic effects into account, linear simulations of kinetic peeling-ballooning mode using the gyro-Landau-fluid model show that this region can be accessed, with the high-beta, low-n modes stabilized. On the other hand, the bootstrap current as well as the kinetic effects decreases the first and second critical beta of ballooning mode stable region.

Simulation of divertor heat flux widths on EAST by BOUT++ transport code*

G. Z. Deng[1,2,3], X. Q. Xu[3], N. M. Li[3,4], L. Wang[1,2,4], X. J. Liu[1,2], T. Y. Xia[1,2] and X. Gao[1,2]

[1] Institute of Plasma Physics, Chinese Academy of Sciences, Hefei 230031, China

[2] University of Science and Technology of China, Hefei 230026, China

[3]Lawrence Livermore National Laboratory, Livermore, CA 94550, USA

[4]School of Physics and Optoelectronic Technology, Dalian University of Technology, Dalian 116024, China

gzdeng@ipp.ac.cn

The BOUT++ edge plasma transport code is applied to simulate the divertor heat flux widths for EAST steady state H-mode discharges. The code is a two-fluid transport code, solving a system of equations for plasma density, electron and ion temperatures, parallel ion flow velocity, parallel current, electrostatic potential and vorticity, with all drifts and the sheath potential in the SOL. Transport coefficients are calculated based on the experimental profiles inside the separatrix and then extending to the SOL region. The simple neutral transport model is used.

The wall and divertor particle recycling boundary conditions are included. The plasma-neutral

interactions taken into account are charge-exchange, ionization and recombination. The simulations of the divertor heat flux widths of EAST steady state H-mode discharges has been carried out by BOUT++ without drifts and neutrals. The heat flux widths from the simulations are in reasonable agreement with the experimental results, however, the widths from both the simulations and experiments turn out to be a factor of 2 larger than Goldston's drift-based model and Eich's multi-machine scaling, which may probably be due to the dominant RF heating on the EAST discharges involved in this work [G.Z. Deng et al., Plasma Phys. Control. Fusion 60 (2018) 045001, T.Y. Xia et al., Nucl. Fusion 57 (2017) 116016]. The simulations with drifts and neutrals will be presented for figuring out their impacts on EAST divertor heat flux widths.

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Basic physics of the first wall

Roman Smirnov

University of California, San Diego, Department of Mechanical and Aerospace Engineering, 9500 Gilman Drive, La Jolla, California 92093-0411, USA

E-mail: rsmirnov@ucsd.edu

At present, fusion energy production in magnetic confinement devices is facing several scientific and technical challenges. Among such challenges, the issues related to interaction of the fusion plasma with the first wall of vacuum chamber, in particular divertor target plates, have been recognized as critical both due to impact of the plasma on longevity of the wall components and due to effects of the wall on the plasma performance. The plasma-wall interactions in fusion environments are very multifaceted and involve a wide variety of plasma conditions and wall materials, facilitating rich physics spanning from atomic to macroscopic spatial and temporal scales. Such, for example, energetic fusion plasma ions and neutrals can penetrate into wall material upon collision causing their accumulation and propagation in the wall components. The buildup of large quantities of plasma gases in the material leads to various microstructural changes, which substantially modify material properties critical for wall operation. In addition, accumulation in the wall of radioactive tritium, which will be used in fusion reactors, presents safety concerns and is strictly regulated. On the other hand, release from the wall of implanted plasma particles controls plasma recycling and erosion of wall components caused by plasma exposure contaminates fusion plasmas with impurities, dramatically affecting fusion performance. In this presentation, the basic physical phenomena occurring during plasma-material interactions and their impact on operation of fusion devices are overviewed, with special attention given to the issues, which are currently unresolved and physics of which is not fully understood. The physical processes are considered in three regions: wall material bulk, plasma-material interface, and plasma sheath, where interconnections between the regions are highlighted. The modeling efforts related to each of the regions and requirements for their integrated simulation are further discussed.

BOUT++ Workshop abstract

Physics of the Pedestal, and Integration with the Core and Boundary

Philip B. Snyder

High performance in tokamaks is achieved via the spontaneous formation of a transport barrier in the outer few percent of the confined plasma. This narrow insulating layer, referred to as a "pedestal," typically results in a >30x increase in pressure across a 0.4-5cm layer. Predicted fusion power scales with the square of the pedestal top pressure (or "pedestal height"), hence a fusion reactor strongly benefits from a high pedestal, provided this can be attained without large Edge Localized Modes (ELMs), which erode plasma facing materials. The overlap of drift orbit, turbulence, and equilibrium scales across this narrow layer leads to rich and complex physics, and challenges traditional analytic and computational approaches. Understanding of the physics of the pedestal and ELMs has improved, via extensive studies of linear instability thresholds, and nonlinear simulations. Development of high resolution diagnostics, and coordinated experiments on several tokamaks, have validated understanding of important aspects of the physics, while highlighting open issues. A predictive model (EPED) has proven capable of predicting the pedestal height and width to ~20-25% accuracy in large statistical studies. This model was used to predict a new, high pedestal "Super H-Mode" regime, which was subsequently discovered on DIII-D, and motivated experiments on Alcator C-Mod which achieved world record, reactor relevant pedestal pressure. The physics of the pedestal depends strongly on interactions with both the core (eg via the global Shafranov shift) and the open field line region (eg particle, neutral and impurity sources and transport). Recent implementation of coupled core-pedestal, and core-pedestal-boundary models within the OMFIT framework, as part of the Advanced Tokamak Modeling (AToM) project, have begun to explore these interactions, revealing important physics that motivates detailed study with BOUT++. We discuss recent research on core-boundary integration, and key directions for future research.

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Tokamak Disruptions

Allen Boozer
Columbia University, ahb17@columbia.edu

Sudden disruptive loss of plasma confinement is characteristic of tokamaks though not of toroidal plasmas in general. The severity of tokamak disruptions follows from the absence of a natural centering of the plasma in the chamber; careful adjustments of the vertical magnetic field are required for position control. When position control is lost, the plasma drifts into the chamber walls on their resistive time scale, approximately 150 ms in ITER. Unless the plasma current is quenched faster, the drift of the plasma into the walls will produce plasma kinking, which drives strong and potentially destructive halo currents. These currents can be avoided by rapid plasma cooling, but anything that makes the current decay faster than 10's of seconds can transfer the plasma current to relativistic electrons, which could be even more destructive to ITER. The success of the ITER mission requires at least a year between major runaway incidents and the success of reactors requires at least a decade. The physics of disruptions, their avoidance, and their mitigation will be reviewed. Critical information that could be obtained from existing experiments will be discussed. *This work was supported by the U.S. Department of Energy, Office of Science, Office of Fusion Energy Sciences under Award Numbers DE-FG02-03ER54696, DE-SC0016347, and DE-SC0018424.*

Hands-on exercises: Six-field two-fluid module

Tianyang Xia
Institute of Plasma Physics, Chinese Academy of Sciences

The 6-field 2-fluid module is a 3D BOUT++ model which has been developed for the tokamak edge plasma turbulence simulations. This model is based on the Braginskii equations with the flute-reduction in the drift ordering. The flux-limiting expression of the parallel thermal conduction is applied for the SOL heat transport. The Landau closure is also compatible with the model. 6-field 2-fluid model has been used in the analysis of ELM, coherent mode/fluctuation and H-mode transient particle/heat flux on the main tokamaks in the world, such as DIII-D, C-Mod, EAST, etc..

This hands-on session will begin with setting up, running and analyzing one 6-field 2-fluid simulation.

Latest developments in BOUT++ boundary plasma turbulent transport simulations

Xueqiao Xu and BOUT++ team
Lawrence Livermore National Laboratory
xu2@llnl.gov

A significant progress has been made recently in BOUT++ simulations development. The results will be summarized here including, but not limited to: (1) Modeling tokamak boundary plasma turbulence and understanding its role in setting divertor heat flux widths. (2) Developed simulation models for density limited disruptions and the resulting scrape-of-layer broadening. (3) ELM crash with nonlinear toroidally axisymmetric flow and field. (4) Derived a Landau fluid closure for arbitrary frequency, implemented and tested in BOUT++ simulations. (5) Performed linear analyses of peeling-ballooning modes in high beta pedestal plasmas. Taking the kinetic effects into account, simulations of kinetic peeling-ballooning mode show the existence of the high beta peeling-ballooning mode stability region. (6) Simulated the ELMs triggering by lithium pellet and its ablation process. Both BOUT++ turbulence and transport codes are used to simulate the divertor heat flux width, which is consistent with experimental Eich scaling for current tokamaks. However, transport simulations show that (1) Drifts and turbulence are locked in a tight competition for C-Mod and a critical SOL transport coefficient is found. (2) ITER & CFETR will possibly operate in a turbulence dominant regime with a heat flux width larger than those extrapolated from the Eich scaling and Goldston HD model sets the lower limit of the width.

Long-legged divertors for confronting tokamak PMI challenges*

M.V. Umansky[1]

with B. LaBombard[2], D. Brunner[2], T. Golfinopoulos[2], A.Q. Kuang[2], M.E. Rensink[1], T.D. Rognlien[1], J.L. Terry[2], M. Wigram[3], D.G. Whyte[2]

[1]Lawrence Livermore National Laboratory, Livermore, CA 94550, USA
[2]MIT Plasma Science and Fusion Center, Cambridge, MA 02139, USA
[3]York Plasma Institute, Dept. of Physics, Univ. of York, Heslington, York, YO10 5DD, UK

Recent modeling of a tightly-baffled long-legged divertor demonstrates a detached divertor regime where energy is dissipated on sidewalls of the divertor leg channel, by combined effect of radial transport and radiation [1]. This fully detached regime is found to be passively stable; it persists for a wide range of input power from the core, and as input power is varied, the location of the detachment front in the leg shifts closer to, or away from, the divertor target. Thus, for a sufficiently long divertor leg, the divertor remains detached, with benign power loads on the material surfaces, and the detachment front is located safe distance away from the target plate and the primary X-point. Calculations demonstrate that a long-legged divertor can accommodate up to an order of magnitude larger exhaust power than a standard divertor can, for otherwise similar parameters. This makes a long-legged divertor a potentially attractive solution for divertor power handling and control in a reactor, and it is currently considered for high-field designs (ADX, ARC). Physical mechanisms and sensitivity to model assumptions are examined for the long-legged detached regime, and its implications for fusion energy are discussed.

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Latest developments in BOUT++ boundary plasma turbulent transport simulations

Xueqiao Xu and BOUT++ teams
Lawrence Livermore National Laboratory
xu2@llnl.gov

A significant progress has been made recently in BOUT++ simulations and developments from our international teams in Us, UK, China, Japan, and Korea. The results will be summarized here including, but not limited to: (1) Modeling tokamak boundary plasma turbulence and understanding its role in setting divertor heat flux widths. (2) Developed simulation models for density limited disruptions and the resulting scrape-of-layer broadening. (3) ELM crash with nonlinear toroidally axisymmetric flow and field. (4) Analyzed scrape-off-layer filament dynamics. (5) Derived a Landau fluid closure for arbitrary frequency, implemented and tested in BOUT++ simulations. (6) Performed linear analyses of peeling-ballooning modes in high beta pedestal plasmas. Taking the kinetic effects into account, simulations of kinetic peeling-ballooning mode show the existence of the high beta peeling-ballooning mode stability region. (7) Simulated the ELMs triggering by lithium pellet and its ablation process. Both BOUT++ turbulence and transport codes are used to simulate the divertor heat flux width, which is consistent with experimental Eich scaling for current tokamaks. However, transport simulations show that (1) Drifts and turbulence are locked in a tight competition for C-Mod and a critical SOL transport coefficient is found. (2) ITER & CFETR will possibly operate in a turbulence dominant regime with a heat flux width larger than those extrapolated from the Eich scaling and Goldston HD model sets the lower limit of the width.

Demonstration of the integration of BOUT++ into the OMFIT framework

T.M. Wilks[1], O. Meneghini[2], S. Smith[2], C. Moynihan[4], O. Izacard[3], X. Q. Xu[5], J. W. Hughes[1]
[1]MIT, [2]General Atomics, [3]PPPL, [4]UIUC, [5]LLNL

BOUT++ has been integrated into the OMFIT framework, which streamlines capabilities of 1) generating meshes 2) deploying scans to remote servers 3) collecting select data 4) monitoring convergence criteria and 5) basic data visualization. Within the OMFIT environment, it is possible to create a workflow for running BOUT++ that begins with the measured data, providing a bridge between the experimental and theoretical understanding of the desired simulation – a powerful tool for experimental and theoretical physicists alike. This presentation will be a hands on demonstration of the capabilities of the OMFIT module developed to run BOUT++, with some discussion on future directions and possible collaborations to expand the platform.