Lodestar - PPPL collaboration on C-Mod Edge Physics: 2012 Progress Report

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INTRODUCTION AND EXECUTIVE SUMMARY

In support of the Alcator C-Mod experimental effort, Lodestar has carried out simulation modeling to better understand a number of topics related to edge physics:

1. the size and scaling of the SOL parallel heat flux width,
2. the nature of the Quasi-Coherent (QC) mode,
3. sheared flows and blob trajectories

The initial work on topics 1 and 2 was carried out in 2010-11, but sensitivity studies and other improvements in the modeling were carried out in 2012, and a paper was written which will be published in the *Physics of Plasmas* in September, 2012. The work on blobs and sheared flow generation was carried out in the present contract period and will be described in detail below. For some topics, parallel modeling was carried out for NSTX (funded under a separate grant) allowing the same physics to be studied under significantly different collisionalities. The focus of topics 1 and 2 was on H-mode shots; the L-mode studies were deferred until later while Ohmic plasmas were studied in topic 3.

As topics 1 and 2 were discussed in detail in last year's progress report and in a paper that will soon be published, this progress report will concentrate on topic 3. Only a brief summary will be given for the other topics. We begin with a brief description of the SOLT code and its reduced model for edge and SOL turbulence.

THE SOLT CODE AND APPLICATIONS TO ALCATOR C-MOD

The SOLT code

The Scrape-Off-Layer Turbulence (SOLT) code[1] is a fluid code that models turbulence in a two-dimensional region perpendicular to the magnetic field **B** at the outboard midplane of the torus. SOLT implements classical parallel physics using closure relations[2,3] for the midplane parallel current and parallel fluxes for collisional regimes ranging from sheath-connected to conduction limited. The SOLT code can describe arbitrarily strong nonlinear plasma dynamics ($\delta n/n \sim 1$), including blob formation, and the physics model supports interchange-type curvature-driven modes, sheath and Kelvin-Helmholtz (KH) instabilities, and drift waves. SOLT also includes the self-consistent evolution of zonal (i.e., poloidally-averaged) flows and has been used to demonstrate the control of turbulence by sheared flows and the radial transport of zonal momentum by turbulent Reynolds' stress. For comparison with experimental gas puff imaging (GPI) data,[4] SOLT includes a synthetic GPI diagnostic which has recently been upgraded to simulate both He and D gas puffs.

SOLT has flexible sources for plasma density, temperature, and flows (n_e, T_e, v_y). In the present work, artificial sources for n_e and T_e are configured to maintain the experimentally observed profiles in the steep pedestal region inside the separatrix. For H-mode simulations, we use an imposed mean sheared flow inside the separatrix, and determine its magnitude by matching the power flowing across the separatrix to that in the experiment. These artificial sources are set to zero in the SOL, so that the SOL profiles themselves are determined self-consistently by the balance between perpendicular turbulent transport and parallel losses. Using the SOLT model, we are able to assess the role of electrostatic turbulence at the midplane in determining the cross-field transport fluxes and midplane profiles.

Size and scaling of the SOL parallel heat flux width

In support of experimental investigations of the size and scaling of the heat flux width for the FY2010 Joint Research Task (JRT) campaign, Lodestar carried out turbulence simulations to better understand the role of cross-field turbulent heat transport in the SOL. We have simulated the scaling of the near-SOL heat flux width, λ_q, with power, P, and plasma current, I_p, on both NSTX[5,6] and C-Mod.[7] By comparing the results, we were able to study the effect of collisionality on the scaling.

For several H-modes on NSTX, the simulated λ_q as well as midplane SOL profiles of density and temperature were compared with NSTX gas-puff imaging (GPI), probe and midplane-mapped divertor infrared thermography (IRTV) data. It was concluded that the midplane turbulence simulated in SOLT explains some, but not all, of the experimentally observed λ_q scaling.

For C-Mod, we modeled an EDA H-mode shot. The SOLT code produced a heat flux SOL width of about $\lambda_q \sim 0.5$ mm, below the experimental result by a factor of 2 – 4 but scaling the same way with power, as discussed in the next paragraph. Most of the edge turbulence was in a single mode with a poloidal wavelength of order 6 cm, which might be related to the quasi-coherent mode. Moreover, the radial particle transport due to this mode was an order unity fraction of the total particle flux, as observed in the C-Mod experiments. This work was written up in the past year and will soon be published.[7]

For both NSTX and Alcator C-Mod, the simulations show significant areas of agreement with the experimental data. An analysis of the relative contributions of the various terms in the SOLT parallel closure model shows that the parallel heat flux just outside the separatrix is in the sheath-connected (collisionless) regime for the NSTX shots analyzed, but it is in the conduction-limited (collisional) regime for the C-Mod EDA H-mode shot. This difference in collisionality leads to different scalings. On C-Mod the SOL width λ_q *decreases* with increasing power (and temperature at the separatrix),[7] whereas λ_q *increases* with power in NSTX.[5] These trends were found in both the experiments and in the simulations and can be explained by the collisionality dependence. More details are available in our published papers.

The Quasi-Coherent (QC) mode

An intriguing result from the SOLT simulations of the C-Mod EDA H-mode is the appearance of a mode that has at least some qualitative similarities to the quasi-coherent mode (QCM) observed experimentally in the EDA regime.[8,9] The wavenumber and frequency spectra of density fluctuations were calculated with SOLT, and the broad features (low-frequency plateau and algebraic high-frequency decaying tail) are typical of both simulation and experimental data for intermittent edge turbulence.

The “quasi-coherent” feature occurs at 600 kHz and $k_{y,max} = 0.8\ cm^{-1}$. This feature results from density fluctuations which originate in the strong gradient region just inside the separatrix, and are convected and Doppler shifted by the $\mathbf{E}\times\mathbf{B}$ flows. The QCM frequency in the lab frame is affected by the radial electric field and toroidal rotation. Although SOLT does not provide a first principles model of these effects, it is encouraging that simulated frequencies are in the range of several hundred kHz, which is characteristic of QCM frequencies seen experimentally. In SOLT, the “QC” mode is responsible for about 48% of the net cross-field particle flux (measured just inside the separatrix at the location of maximum radial flux); this fraction is in good agreement with the experimental value. Thus, the QC mode is a key player in setting the SOL width in the simulated EDA H-mode.

Motivated by a desire to understand the physics of the QCM, especially the nature of this cascade barrier, we have explored the transfer of energy between eigenmodes of the saturated turbulent profiles. A linear analysis reveals interplay between underlying drift-interchange, Kelvin-Helmholtz and sheath-driven instabilities. This work will be continued in the next project period if it is funded.

SHEARED FLOWS AND BLOB TRAJECTORY STUDIES ON ALCATOR C-MOD

Introduction

Edge sheared flows are thought to be important for turbulence regulation, (e.g. the L-H transition), and furthermore they influence the character of emitted blob-filament structures[2,3] which ultimately contact plasma-facing components. To study the dynamics of blob-filaments and sheared flows, we employ both SOLT code[1] numerical simulations and experimental data analysis [in collaboration with W. M. Davis, S. J. Zweben (PPPL); and B. LaBombard, J. L. Terry (MIT)].

Ongoing theoretical studies (supported by separate funding) have shown that the strong radial inhomogeneity present in the edge and SOL region of a tokamak plasma leads to several mechanisms for sheared flow generation and blob-flow interaction.[10] These mechanisms are related to shearing and rotation or tilting deformations of the blob structures due to various effects:

1) radial variation of the group velocity on the scale of the blob radius due to steep profiles and or rapid changes in topology across the separatrix which shear and rotate the blob charge dipole, [2,3] converting radial blob motion into poloidal motion;
2) a net monopole blob potential due to adiabatic electron physics ($\delta n \sim \delta\Phi$) which induces rotation of the blob charge dipole, mixing radial and poloidal blob motion;
3) asymmetry in the +/- parallel currents when the blob crosses the separatrix (due to the +/- asymmetry of the sheath current-voltage relation) which causes the blob to charge positive and partially rotate, again converting radial motion into poloidal motion; [11]
4) blob rotation as the blob enters the SOL due to finite blob T_e which induces an internal blob radial electric field;[12]
5) interaction of the blob with an existing E×B shear layer (vortex merging and charge dynamics: +/- regions of the blob charge dipole are repelled or attracted by +/- regions of vorticity (charge) in the shear layer).

These mechanisms have well-known counterparts in traditional nonlinear Fourier-wave theory,[13,14] but it is illuminating to see them at play in the context of coherent blob structures. Moreover, blob structures are readily detectable by the gas puff imaging

(GPI) diagnostic[15] enabling an entirely new kind of comparison between theory and experiment.

Blob flow generation and interaction mechanisms were simulated and compared in selected shots under the very different conditions present in NSTX and Alcator C-Mod. In the NSTX work (also supported by separate funding) we have shown that the theoretically predicted mechanisms provide a satisfactory explanation of the observed sheared flow, i.e. for a plasma which is in the more collisionless, sheath-connected limit. Alcator C-Mod provides the important opportunity, under the present sub-contract, of similar blob-flow studies in a much more collisional, sheath-disconnected (i.e. high recycling) case. We conclude that a combination of collisionally-induced disconnection and flow (or equivalently charge) dissipation are require to model the selected C-Mod shot. Possible sources of dissipation are identified.

The simulations use the fluid-based 2D curvature-interchange model embedded in the SOLT code.[1] A blob-tracking algorithm[16] has also been developed and applied to NSTX and Alcator C-Mod data. The algorithm is based on 2D time-resolved images from the GPI) diagnostic. The algorithm detects and tracks local spatial maxima in the normalized GPI signal $I_{gpi}/\langle I_{gpi}\rangle$ where $\langle I_{gpi}\rangle$ is the time-averaged GPI intensity at a given spatial pixel location. In the following, for sake of brevity we will refer to all such tracked objects as *blobs*; however, it should be kept in mind that the detection algorithm is also tracking wave crests and other structures, only some of which are ultimately ejected into the SOL as blob-filaments. The algorithm is able to track both the blob motion and changes in blob structure, such as elliptical deformations, that can be affected by sheared flows.

In the following, results of both seeded blob simulations and fully developed turbulence simulations are compared with experimental data to determine the role of blob and plasma parameters on the blob tracks and to evaluate the exchange of momentum between the blobs and flows. This work will be reported in a poster[17] at the upcoming 2012 IAEA meeting, and in an invited talk[18] at the 2012 DPP-APS meeting.

Experimental shot information and data analysis

Our work on C-Mod was motivated in large part by the observation that typical NSTX low collisionality discharges showed strong mean flows reversing near the separatrix, while a high collisionality C-Mod discharge showed much weaker flows. A particularly striking contrast is shown in Fig. 1. The poloidal v_y data is obtained by tracking the blob motion frame-to-frame in the GPI images, recording the radial location of the blob at that instant in time, and radially binning the data to obtain statistical averages. In each case, the deviations from the mean velocity are at least as large as the mean itself, but for the C-Mod shot, the mean is essentially zero. Parameters for these shots are given in Table 1.

Sheared flows in Ohmic and L-mode plasmas are thought to be generated by the turbulent Reynolds Stress (RS). Information about the RS can be obtained from blob tracking data in two ways. One method is to follow the trajectory of an individual blob structure in time. The acceleration, $a_y = dv_y/dt$ along its path is essentially the Reynolds force per unit mass. Averaging over a statistical sample of blobs in a given radial bin gives the radial structure of the Reynolds force

$$\langle a_y \rangle = \left\langle \frac{dv_y}{dt} \right\rangle = \langle \mathbf{v} \cdot \nabla v_y \rangle = \frac{\partial}{\partial x} \langle v_x v_y \rangle \tag{1}$$

where the quantities $\langle a_y \rangle$ and $\langle dv_y/dt \rangle$ are computed from averages of "single-particle" blob trajectories while $\langle \mathbf{v} \cdot \nabla v_y \rangle$ and $\partial_x \langle v_x v_y \rangle$ are regarded as statistically averaged fluid quantities. Results for $\langle a_y \rangle$ from both experimental data and simulations will be presented in the next sub-section.

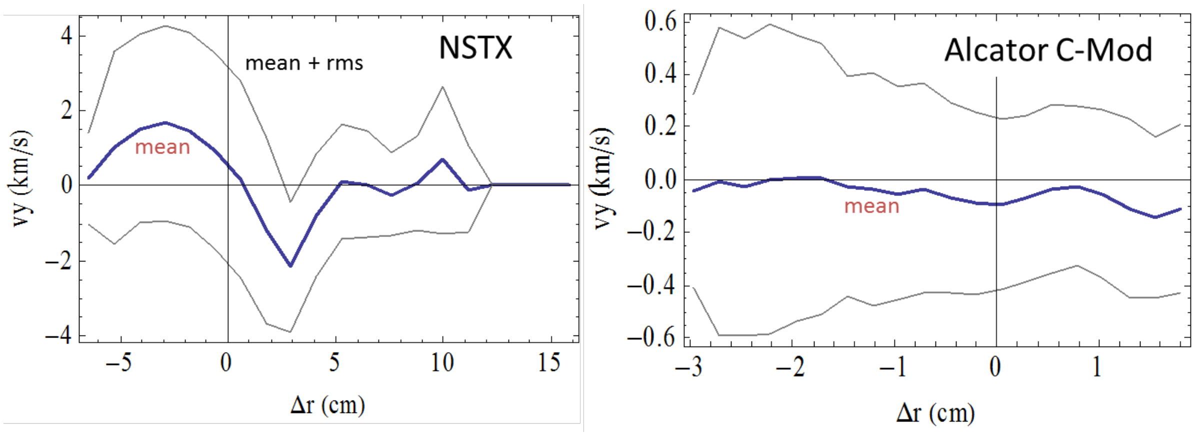

Fig. 1 Comparison of poloidal (v_y) blob velocities measured in an NSTX low collisionality discharge, and an Alcator C-Mod high collisionality discharge. The thick blue line is the mean v_y of all blobs in the given radial bin. The thin gray lines above and below indicate the mean ± the rms deviation.

	NSTX 139444	Alcator C-Mod 1100824017
comment	ohmic	ohmic high ν_{ei}
$n_{e,sep}$ (cm^{-3})	5.8×10^{12}	1.0×10^{14}
$T_{e,sep}$ (eV)	19.	47.
$\rho_{s,sep}$ (cm)	0.26	0.025
$\Lambda_{SOL} \sim \nu_{e*}(m_e/m_i)^{1/2}$	0.3 – 0.8	1-3
blob size $a_{b,sep}$ (cm)	2.2 ± 0.5	0.4 ± 0.1
blob amp $\delta I/\langle I\rangle\vert_{sep}$	0 – 1.6	0 – 0.6

Table 1 Shot parameters. $\Lambda_{SOL} > 1$ implies strong collisionality and parallel blob disconnection from the sheaths.

A second method for obtaining information about the RS is made possible by a feature of the blob tracking algorithm that allows detection and tracking of changes in elliptical deformations of the blob structure. We assume that the ellipticity and tilt angle of the blob electrostatic potential are similar to those of the density and temperature, and hence the GPI emission, notwithstanding the detailed differences in internal structure (the blob density and temperature have a monopole structure, whereas the potential has a characteristic dipole structure[2,3]). Given this assumption, it can be shown that a normalized proxy for the RS, hereafter referred to as RS′ is given by

$$RS' = -\sin(2\theta)[1-(r_2/r_1)^2] \tag{2}$$

where θ is the tilt angle (measured clockwise from the positive Δr axis) and r_2 (r_1) is the major (minor) axis of the best-fit ellipse. In the absence of either ellipticity or tilt, there is no Reynolds stress.

Figure 2 shows the results of an RS′ analysis for the same NSTX and Alcator C-Mod shots of Fig. 1 and Table 1. The spatial derivative $-\partial_x RS'$ is proportional to the Reynolds force. It follows that the mean Reynolds force for the NSTX shot is consistent with the observed direction of the mean flows in Fig. 1. For the C-Mod shot, the mean Reynolds force is essentially zero, again consistent with the small flows observed in Fig. 1. A different analysis method of zonal flows for this (and other) Alcator C-Mod shots was described in Ref. 19. Small mean zonal flows were also reported for this C-Mod shot (1100824017), and the oscillating zonal flows were found to have a broadband frequency spectrum.

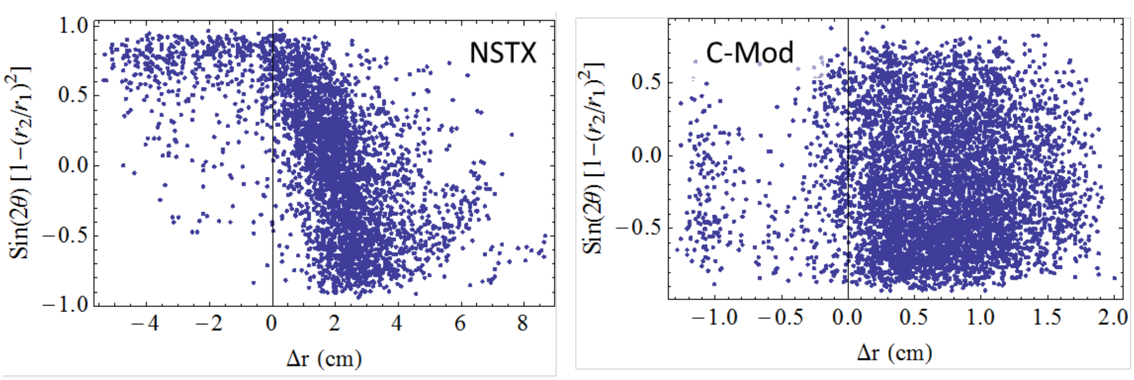

Fig. 2 Proxy for the Reynolds stress for the NSTX and Alcator C-Mod shots shown in Fig. 1.

It is significant that for both the NSTX and C-Mod shots, an order unity variation of RS′ (essentially from -1 to 1, i.e. over the full possible range) is observed. This shows that significant instantaneous shearing stresses are acting on the fluid. In previous theoretical and simulation work[1] we have shown that order unity shearing deformations of the blob structure are consistent with the idea that shearing affects the blob dynamics, i.e. $\omega'_E \sim \gamma$ where γ is a characteristic linear growth rate or inverse auto-correlation time, and ω'_E is the shearing rate. When the shearing rate is of this magnitude or larger, it both creates isolated blob structures from radial streamers[1,20] and begins to suppress turbulent radial transport.

Motivated be these observations, we carried out interpretive simulations of the two shots using the SOLT code. Both initial value seeded-blob simulations and turbulence simulations run to a quasi-steady state were performed. Details of the NSTX simulations will be reported elsewhere; main results are given here to contrast with the C-Mod case.

Seeded blob simulations with SOLT

The seeded blob simulations were run as a SOLT initial value problem. Smoothed experimental plasma profiles of density and temperature were employed together with other machine parameters that enter the SOLT model: magnetic field B, major radius R, and connection length profile $L_{||}$. Dissipation parameters (plasma viscosity, and flow damping) were treated as free parameters. The viscous diffusion coefficient was somewhat arbitrarily set to 0.2 D_B where D_B is the Bohm diffusion coefficient to inhibit the formation of small scale structures ($< \rho_i$) for which both the numerical grid and the physics model are inaccurate. The flow damping (friction) parameter ν was varied as discussed below. Typical blob spatial sizes, amplitudes, and birth locations were extracted from the experimental dataset. A Gaussian blob with the given properties was then superimposed on the plasma profiles as an initial condition for the SOLT simulation. The blob was tracked until it either disappeared (i.e. lost its structure) or travelled radially to a limiter in the far SOL. The acceleration a_y was computed as a function of radial position and compared with experimental data. Results are shown in Fig. 3.

As discussed in a previous section, the SOLT code is a 2D turbulence code which simulates filamentary structures in the 2D plane perpendicular to the magnetic field B. Parallel dynamics are modeled by analytic closure relations[2] which, for example, model the parallel confinement time of particles and energy depending on the parallel connection length to the divertor, plasma collisionality, etc. Simulations are usually interpreted as applying at the outboard midplane of the tokamak, near where most of the experimental diagnostics are located. When the NSTX case is initialized with midplane plasma and machine parameters and a typical blob, the resulting a_y provides a convincing fit to the data, showing significant negative acceleration as the blob moves from the edge across the separatrix and into the SOL.

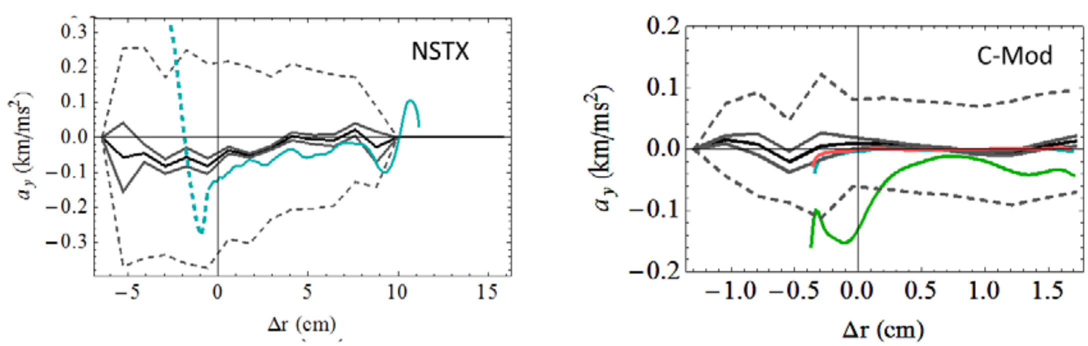

Fig. 3 Reynolds force $\langle a_y \rangle$ for seeded blob simulations compared with experimental results for NSTX and Alcator C-Mod. The black/grey curves are experimental data. The central black curve is the mean acceleration, with statistical uncertainties shown by the nearby solid grey lines. The dashed grey lines show the mean ± rms deviations for the experimental data. Colored curves are from the SOLT seeded blob simulations. The colored dashed portion of the NSTX simulation is the result of an unphysical initial transient as the seeded blob relaxes. See text for an explanation of the C-Mod simulation cases.

For the highly collisional C-Mod case, SOLT simulations are more challenging because collisionality allows the blob filaments to acquire structure (e.g. temperature gradients) along the magnetic field line. When seeded blob simulations were carried out for the C-Mod case using midplane values, and no flow damping, significant a_y resulted, as shown by the green curve in Fig. 3. The C-Mod experimental result of near-zero a_y could be modeled satisfactorily only by making several additional assumptions: complete parallel sheath disconnection in the SOL, partial collisional disconnection in the edge, and finite flow damping, $\nu/\Omega_i = 0.02$ (blue, almost hidden) or 0.03 (red). Theoretically, in our model, flow damping is equivalent to friction and also to extra charge dissipation by cross-field currents.[2,3] The latter are expected when X-points (and their associated thin radial fans[21]) are present downstream along B. With these simulation parameter choices, an acceleration is obtained that is within the experimentally observed band.

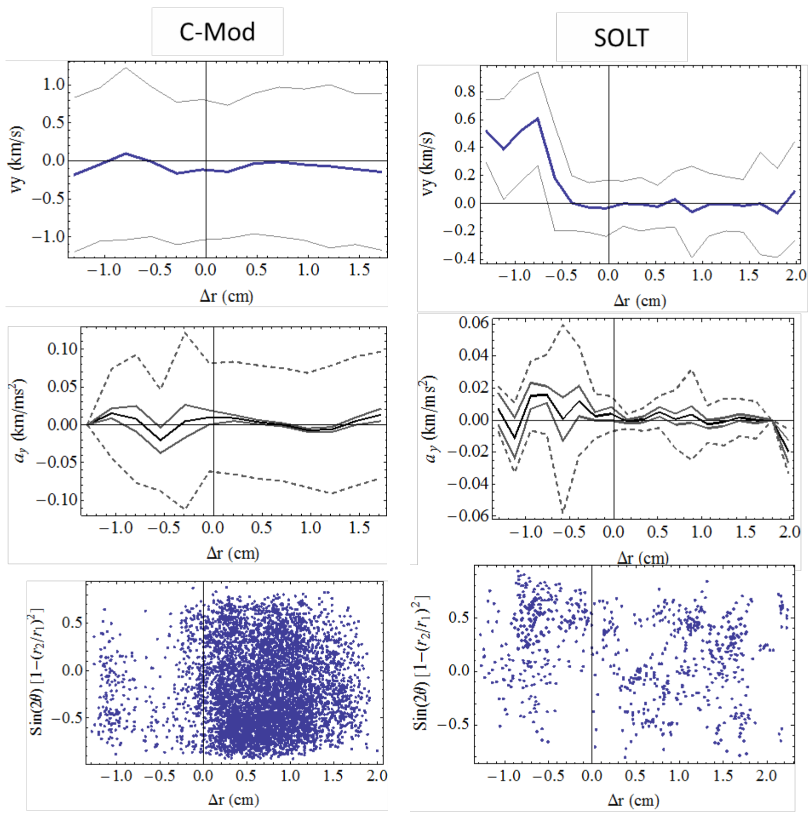

Fig. 4 Comparison of SOLT turbulence simulation (right) with Alcator C-Mod data (left). Upper panels show the mean (thick blue) and rms deviations of the blob velocity v_y as measured by blob-tracking. Middle panels show the mean blob acceleration $a_y = dv_y/dt$ taken along the blob trajectory (thick black) together with its statistical uncertainty (nearby solid gray) and its rms deviation (dashed). Bottom panels show the Reynolds stress proxy RS′.

Turbulence simulations with SOLT

Using the same input parameters as for the seeded blob simulation just discussed, in particular $\nu/\Omega_i = 0.02$, the SOLT code was allowed to run to a quasi-turbulent steady state. In this mode of operation, it is necessary to supply source terms to replenish the edge profiles that are depleted by the turbulent transport. In SOLT, this is accomplished by adding a source term that relaxes the turbulent profiles back to the reference experimental profiles at a specified rate. Typically, the relaxation rate is set to be small or zero in the SOL; however, in the present C-Mod simulations it was found that this resulted in a high temperature ($T \sim T_{sep}$) "shelf" or plateau in the SOL. This unrealistic elevated temperature had a unphysical effect on the synthetic He GPI diagnostic used to compare SOLT with the experimental data. To overcome this, the present simulations were run with an-hoc energy sink in the SOL. We speculate that the energy sink could be related to ionization and radiation cooling which at present is not explicitly modeled in SOLT. It is interesting that neutrals in the SOL would not only be consistent with ionization/radiation cooling. but might also contribute through ion-neutral collisions to flow damping.[22]

Results of the turbulence simulation are shown in the right panels of Fig. 4, to be compared with the experimental results in the left panels (which for convenience repeat results given previously in Figs. 1, 2 and 3). For these comparisons, the synthetic GPI signal from SOLT was converted to the same format as the GPI camera images from the experiment, and processed using the same blob-tracking software. The upper two panels show the mean blob velocity vs. radial distance from the separatrix. The mean velocity is nearly zero in both the experiment and the simulation except that near the left (core-side) radial boundary, the SOLT result shows a velocity in the electron diamagnetic drift direction. This may be an artifact of the core-side boundary condition which sets the mean **E**×**B** velocity to zero, and thus leaves the blobs (local wave crests) near the left boundary to acquire the local (positive) phase velocity of the electron drift wave. The rms velocity fluctuations are somewhat larger in the experiment than in the simulation. The middle panels shows the acceleration a_y which is proportional to the Reynolds force. The simulation, like the experiment, produces nearly zero a_y to within statistical uncertainty. However, the rms a_y fluctuations are also larger in the experiment than in the simulation. Finally, the lower panels compare the Reynolds stress proxy, RS′. Although the statistics for the simulation are poor (because the simulation has not yet been run for the same length of time as the data, i.e. 20 ms) it can be seen that the full range (-1 to 1) of the RS′ space is filled and the simulation, like the experiment, shows little evidence for spatial variation of RS′.

Sensitivity studies reveal that the most important parameter for achieving small flows is the damping (charge dissipation) parameter ν. It is of course trivial that a sufficient large value of flow dissipation reduces the mean simulated blob flows ($\langle v_y \rangle$ in the upper panel) to near zero. However, it is significant that this level of damping does not also destroy the turbulence. The RS′ plot indicates that this simulation is still strongly turbulent, but unlike the NSTX case, here the turbulence does not organize strongly enough to generate significant mean flows.

Conclusions

A combination of experimental data analysis, seeded blob simulations, and turbulence simulations have been used to study the interaction of blobs with sheared flows. Theoretical mechanisms related to radial inhomogeneity and the subsequent generation of the Reynolds stress are sufficient to explain the observed generation of blob poloidal flows (their size, radial scale, direction and reversal across the separatrix) in a low collisionality NSTX shot. A selected high collisionality Alcator C-Mod shot shows very small mean sheared flows. It was found that many characteristics of this shot could be simulated by additionally assuming (i) collisional disconnection of the midplane from the divertor sheaths, and (ii) flow damping or equivalently charge dissipation by radial currents. The former assumption is justified based on the collisionality parameters of the discharge. It was speculated that the latter assumption may be consistent with either X-point effects or neutral collisions.

SUMMARY

In the past contract period, we have collaborated with J. Terry and B. LaBombard (MIT) and S. Zweben and W. Davis (PPPL) to compare GPI data from Alcator C-Mod with SOLT simulations of seeded blobs and fully-developed turbulence. The project also used a new blob tracking algorithm developed by Davis.[16] This work concentrated on both Alcator C-Mod EDA H-mode and Ohmic plasma shots. Important results include:

- discovery of a quasi-coherent mode in the EDA H-mode simulations, which has several qualitative features in common with the experimental one;
- identification of physical mechanisms that allow blobs to drive sheared flows;
- study effects of collisionality by comparing C-Mod and NSTX cases.

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