First results of global mesoscale electromagnetic turbulence simulations in MAST

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Introduction

- Computational models of tokamak plasma transport must resolve length scale of turbulence L, which is typically of order ρ_i (ion Larmor radius) or less
- Hot spherical tokamak (ST) plasmas such as MAST have high normalised Larmor radius $\Rightarrow$ relatively straightforward to perform global fluid simulations on confinement timescales
- Microturbulence on sub-ρ_i scale in MAST has been modelled using gyrokinetic approach[1]
- First global mesoscale ($L \sim \rho_i \rightarrow$ system size) electromagnetic turbulence simulations of MAST have been performed using new two-fluid code `CENTORI` (**C**ulham **E**mulator of **N**umerical **TORI**)[2]
- `CENTORI` is successor to `CUTIE`:
  - two-fluid electromagnetic turbulence code based on periodic cylinder model
  - restricted to large aspect ratio plasmas with circular cross-section
  - shown to reproduce LH transition via control of particle fuelling in COMPASS-D[3]
- `CENTORI` applicable to tokamak plasmas with arbitrary R/a & high β ; intended to be used for simulation of global turbulence on confinement timescales in conventional tokamaks (including JET & ITER) as well as STs

[1] Roach *et al.* PP&CF **51**, 124020 (2009)

[2] Knight *et al.* Comput. Phys. Comm., submitted (2011; arXiv:1109.173)

[3] Thyagaraja *et al.* Phys. Plasmas **17**, 042507 (2010)

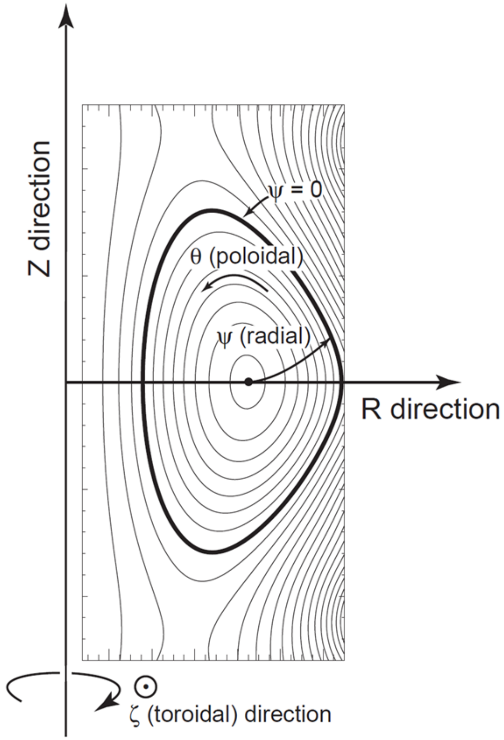
CENTORI coordinate system

- GRASS (**GRA**d-**S**hafranov **S**olver), a subroutine of CENTORI, is used to co-evolve equilibrium poloidal flux Ψ

- Equilibrium used to define quasi-orthogonal plasma coordinates (ρ,θ,ζ) with $\rho \propto \Psi$, $\rho \in [0,1]$, $\nabla\rho \cdot \nabla\theta \neq 0$ in general; Jacobian from laboratory to plasma coordinates taken to be flux function:

$$J \equiv \nabla\zeta \cdot (\nabla\rho \times \nabla\theta) = J(\Psi)$$

- generalisation of Hamada coordinates:[1] speeds up vector operations & evaluation of flux surface averages



[1] Hamada Nucl. Fusion **2**, 23 (1962)

CENTORI two-fluid model

$$m_i n_e\left(\frac{\partial \mathbf{v}_i}{\partial t}+\mathbf{W}\times\mathbf{v}_i\right) = -\nabla p_i - \frac{m_i n_e}{2}\nabla v_i^2 + en_e\mathbf{E} + \frac{en_e}{c}\left(\mathbf{v}_i\times\mathbf{B}\right) - en_e\eta\mathbf{J} - m_i n_e \chi_v \nabla\times\mathbf{W} + \mathbf{S}_v$$

vorticity ($\nabla\times\mathbf{v}_i$)

velocity diffusivity

$$\mathbf{0} = -\nabla p_e - en_e\mathbf{E} - \frac{en_e}{c}\left(\mathbf{v}_e\times\mathbf{B}\right) + en_e\eta\mathbf{J}$$

$$\frac{3}{2}n_e\left(\frac{\partial}{\partial t}+\mathbf{v}_i\cdot\nabla\right)T_i + p_i\nabla\cdot\mathbf{v}_i = -\nabla\cdot\mathbf{q}_i + S_i$$

$$\frac{3}{2}n_e\left(\frac{\partial}{\partial t}+\mathbf{v}_e\cdot\nabla\right)T_e + p_e\nabla\cdot\mathbf{v}_e = -\nabla\cdot\mathbf{q}_e + S_e$$

$$m_i\left[\frac{\partial n_e}{\partial t}+\nabla\cdot\left(n_e\mathbf{v}_i\right)\right] = S_n - \nabla\cdot\Gamma_{\mathbf{W}} + \delta_n - m_i\nu_{i\parallel}\left(n_e - \langle n_e\rangle\right)$$

parallel relaxation rate

diffusion term

Ware pinch term

$$\frac{1}{c}\frac{\partial \mathbf{A}}{\partial t} = -\mathbf{E} - \nabla\Phi$$

$$\mathbf{B} = \nabla\times\mathbf{A}$$

$$\mathbf{J} = \frac{c}{4\pi}\nabla\times\mathbf{B}$$

Solution of equations in CENTORI

- At present only ζ component of **A** (=-Ψ) is evolved; resistivity in induction equation assumed to be neoclassical
- Energy equations have conductivities that include neoclassical & electromagnetic turbulence terms; latter are linear functions of $\delta\mathbf{W}^2$ (enstrophy) & $\delta\mathbf{J}^2$
  - turbulent diffusion terms model effect of fluctuations on subgrid scales (cf. large-eddy simulations in meteorology[1])
- Similar diffusivities used in continuity & momentum equations
- At present particle, momentum & heating sources are specified flux functions, rather than taken directly from experiment
- Derivatives in all coordinates (ρ,θ,ζ) & time approximated by finite differences
  - solution method entirely non-spectral
  - parallelisation of code is then straightforward[2]

[1] Lesieur *et al.* Large-Eddy Simulations of Turbulence, Cambridge University Press (2005)

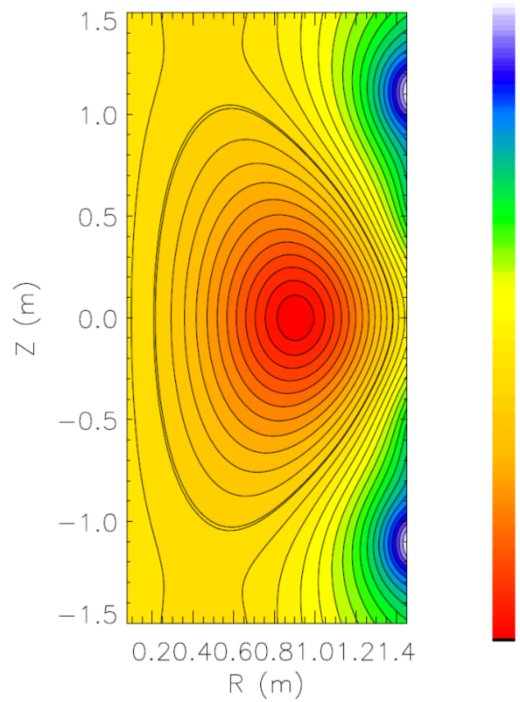
[2] Knight *et al.* Comput. Phys. Comm., submitted (2011; arXiv:1109.173)

CENTORI equilibrium

- GRASS subroutine of CENTORI is free-boundary Grad-Shafranov solver: takes into account currents in poloidal field coils
- Currently only simplest form of Grad-Shafranov equation, applicable when flows are subsonic, is used:

$$R\frac{\partial}{\partial R}\left(\frac{1}{R}\frac{\partial \Psi}{\partial R}\right)+\frac{\partial^2 \Psi}{\partial Z^2}=-4\pi R^2 p'-FF'$$

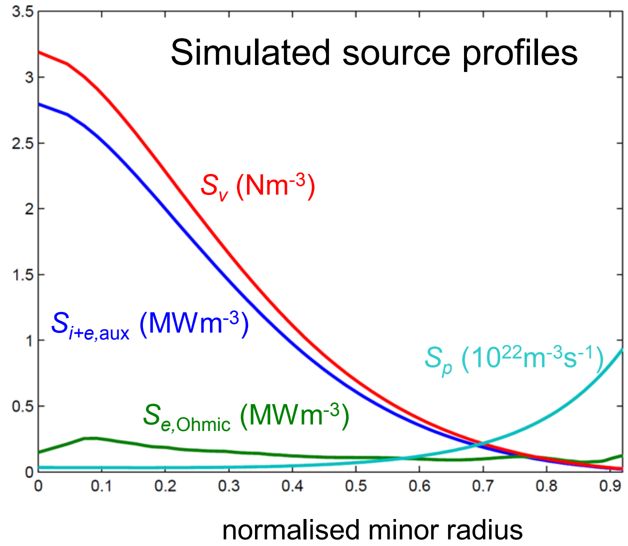
  where $F = RB_\varphi$
- Grad-Shafranov equation solved numerically by Fourier analysing in Z & computing "steady-state" solutions of one-dimensional diffusion equation with pseudo-time derivative



MAST-like equilibrium computed using GRASS

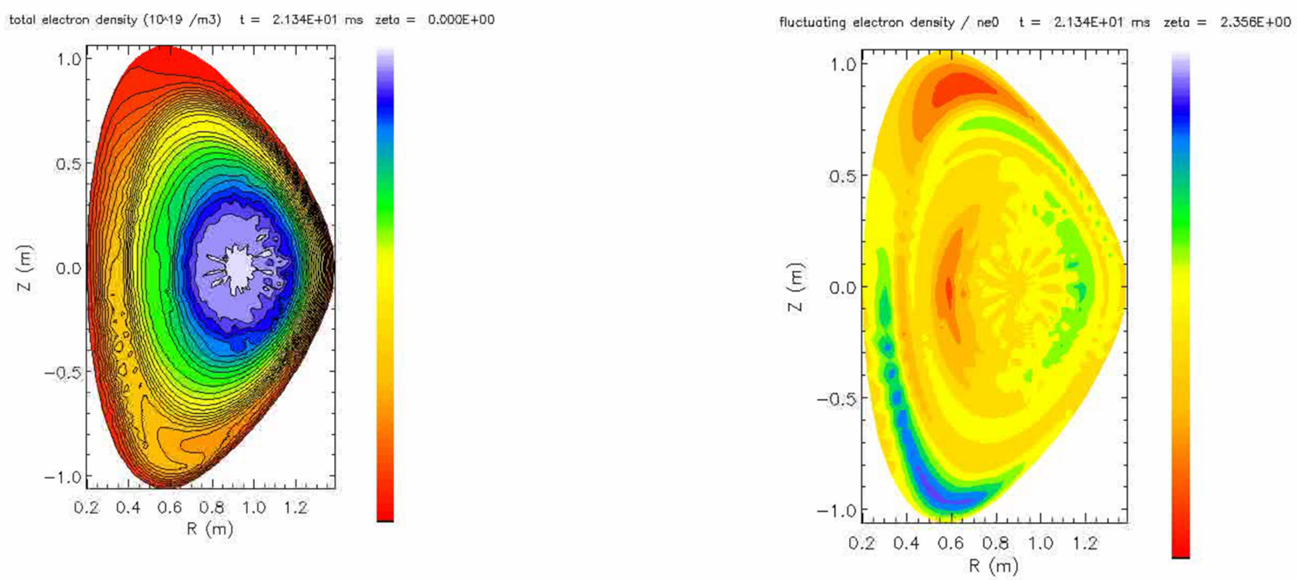
CENTORI simulations of MAST

- L-mode MAST-like plasma simulated using CENTORI for ~20ms (~ typical energy confinement time): $R \approx 0.9$m, $a \approx 0.65$m, $B_\varphi \approx 0.5$T, $I_p \approx 1$MA, auxiliary power = 2.8MW
- After 20ms equilibrium profiles appear to be approaching steady state
- In MAST auxiliary heating & momentum drive are provided by two neutral beams; simulated profiles ($S_{i+e,aux}$ & S_v) assumed to be identical & centrally-peaked
- Ohmic heating power << $S_{i+e,aux}$ except close to edge



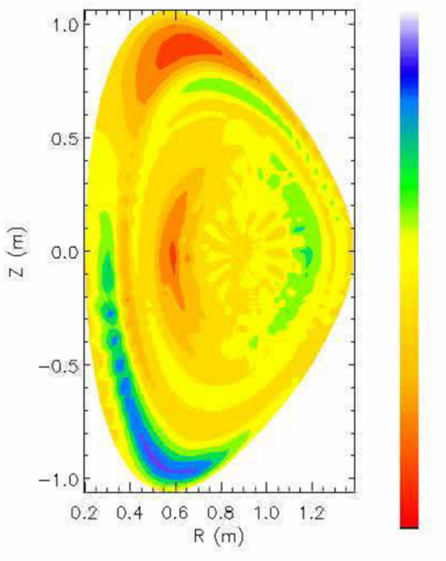
- Feedback mechanism used to control volume-averaged density; fuelling rate (S_p) peaks close to edge
- Typically 129×65×65 grid points in (ρ,θ,ζ) domain; 1ms of plasma evolution can be simulated using 256 MPI processes in ~12 hours

Electron density fluctuations (1)



- In simulation high *m* electromagnetic mode occurs in plasma core ($q < 1$, but no sawtooth crash occurs within simulated time)
- Fluctuation results will be used to generate synthetic beam emission spectroscopy (BES) data for comparison with MAST measurements (cf. Brian Lloyd's talk at this conference)

Electron density fluctuations (2)



- $n = 0$, $m \neq 0$ mode in simulation peaks at $\theta \approx \pm 90°$, $\nu \approx 20\text{kHz} \approx c_s/2^{1/2}\pi R$ (c_s - sound speed)
  - **Geodesic acoustic mode** (GAM): due to toroidal coupling between $m = n = 0$ component of $\delta\Phi$ & $m = 1$, $n = 0$ component of δn_e
  - In large aspect ratio circular cross-section limit[1]

$$\frac{\delta n_e}{n_e} = -\sqrt{2} k_r \rho_i \frac{e\delta\Phi}{T_e} \sin\theta$$

    k_r – radial wavenumber
  - Potential fluctuations in MAST experiments have been identified as GAMs[2]

- Steady inboard/outboard asymmetry at mid-radius due to centrifugal force: if T_e, T_i are flux functions

$$\frac{\partial \ln n_e}{\partial \theta} = \frac{1}{2} M_\varphi^2 \frac{\partial \ln R}{\partial \theta}$$

  M_φ (sonic Mach number) ≤ 0.4 in this simulation

[1] Diamond *et al*. PP&CF **47**, R35 (2005)

[2] Robinson *et al.* PRL, submitted (2011)

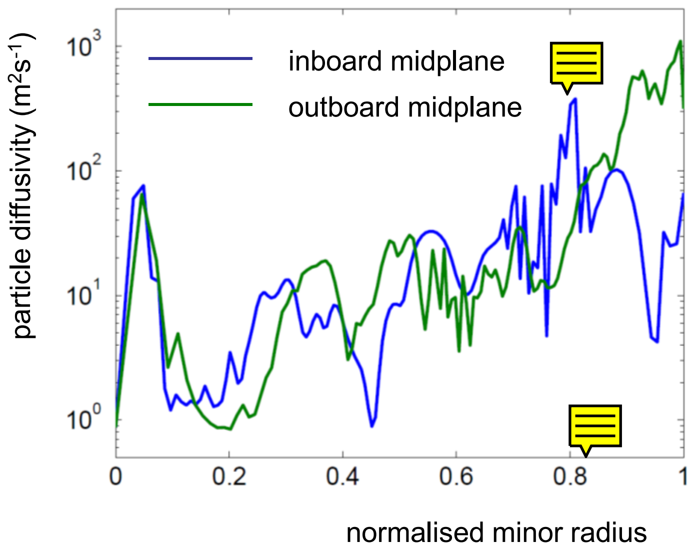
Particle transport

- In simulation strongly turbulent particle transport (D ~ 60-70 m^2s^{-1}) occurs in conjunction with electromagnetic mode close to axis (r/a < 0.1)

- Transport falls to ~ neoclassical level at r/a ~ 0.1-0.2

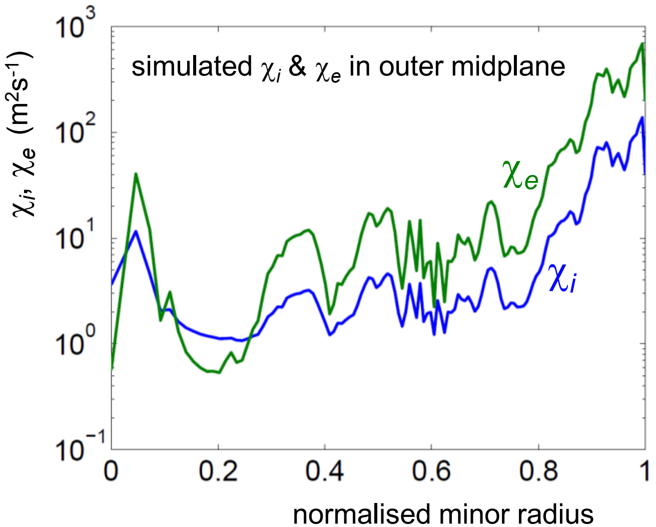
- Close to plasma edge, diffusivity is up to 10^2 times higher on low field side than on high field side

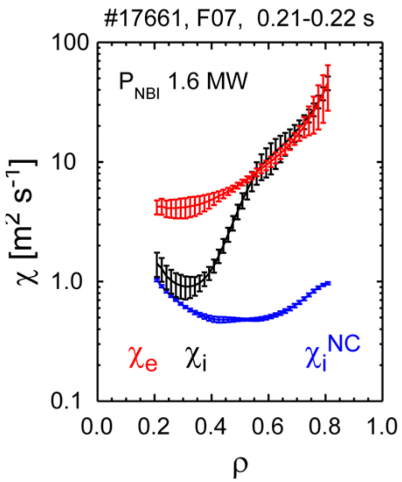
  - turbulence close to edge strongly-ballooning in character



Energy transport

- Simulated conductivity profiles similar to those of particle diffusivity; χ_e & χ_i close to plasma edge significantly lower on high field side
- Experimentally, $\chi_e \geq \chi_i$ in L-mode MAST plasmas with χ_i exceeding neoclassical levels[1] unless internal transport barriers are present[2]
- Profiles & absolute values of χ_e & χ_i broadly similar to experiment



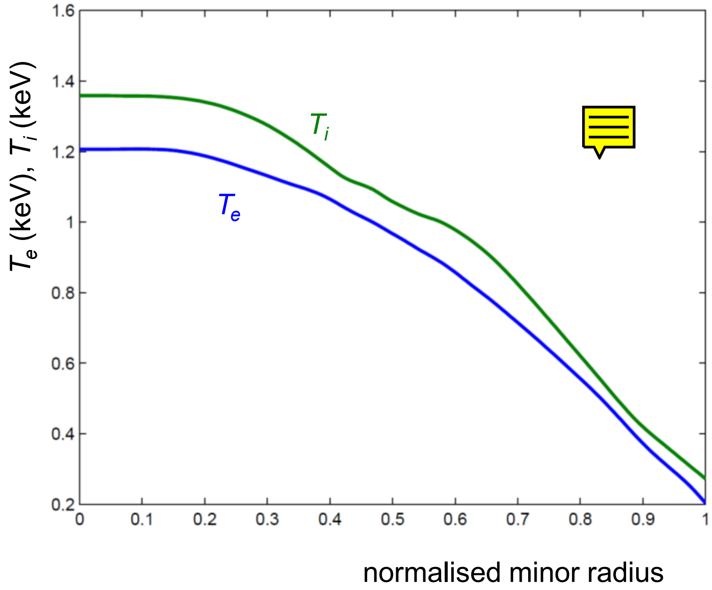


χ profiles from TRANSP modelling of MAST shot 17661 (acknowledgments to A R Field, CCFE)

[1] Field *et al*. 20th Proc. Fusion Energy Conf. EX/P2-11(2005)

[2] Field *et al.* Nucl. Fusion **51** 063006, (2011)

Temperature profiles



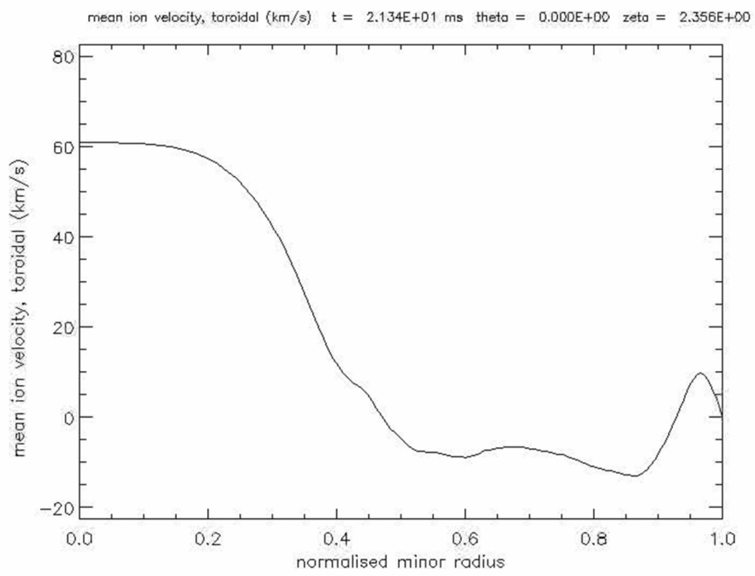
- Simulated auxiliary power partitioned equally between electrons & ions, & all Ohmic power goes into electrons
- Plot shows T_e & T_i in simulation, averaged spatially over flux surfaces & temporally over 0.5ms
- $T_i > T_e$ possibly due to stochastic electron heat transport in turbulent **B** field[1]

- Experimental measurements indicating $T_i > T_e$ in MAST have been attributed to electron temperature gradient (ETG)-driven turbulence[2]
  - occurs on scales ~ ρ_e & hence cannot be modelled using `CENTORI`
  - simulation suggests that additional processes could produce $T_i > T_e$

[1] Rechester & Rosenbluth PRL **40**, 38 (1978)

[2] Roach *et al.* PP&CF **51**, 124020 (2009)

Toroidal velocity profile



- Animation shows simulated flux surface-averaged toroidal velocity profile
- Edge fluctuation correlated with GAM discussed previously
- At high radius $v_\varphi < 0$ (counter-current direction), despite co-current momentum deposition
  - may be due to turbulent stresses (cf. toroidal flows in Ohmic JET plasmas[1])
- Profile broadly consistent with MAST data; counter-current flows are not normally observed when beam injection is co-current, but profile has not yet reached steady state

[1] Nave *et al.* Proc. 37th EPS Conference on Plasma Physics O4.122 (2010)

Conclusions

- First mesoscale simulation of electromagnetic, nonlinearly-saturated turbulence & transport in spherical tokamak plasma (MAST) has been performed using new two-fluid global plasma turbulence code (`CENTORI`)
- Simulation of L-mode plasma over timescale ~ energy confinement time includes self-consistent co-evolution of:
  - mesoscale turbulence
  - density, ion & electron temperature, current & flow profiles
  - free-boundary equilibrium, taking into account X-points & external coils
- Geodesic acoustic mode (GAM) seen in simulation at top & bottom of plasma, in broad agreement with theoretical predictions in large aspect ratio limit; GAMs also identified in MAST experimental data
- Diffusive transport coefficients approximately neoclassical close to core (~1 m^2s^{-1}) & highly turbulent at edge, particularly on low field side (~ 10^2 m^2s^{-1}), reflecting strongly ballooning character of turbulence close to edge
- In simulation $T_i > T_e$, in broad agreement with MAST experimental data
- Simulation provides proof-of-principle demonstration that mesoscale spherical tokamak turbulence & associated transport can be practically modelled using electromagnetic fluid codes such as `CENTORI`